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DEVELOPMENT OF LOW TEMPERATURE GAS GENERATOR TECHNOLOGY

Final Report

Dr. Donald R. Poole
Rocket Research Corporation
Seattle, Washington

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Air Force Rocket Propulsion Laboratory
Research and Technology Division
Air Force Systems Command
Edwards, California

2

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FINAL REPORT

Dr. Donald R. Poole

FOREWORD

This technical report was prepared for the Air Force Rocket Propulsion Laboratory, Research and Technology Division, Edwards Air Force Base, California, by Rocket Research Corporation, Seattle, Washington, under Contract AF 04(611)-11376. This Final Report covers the period January 3, 1966, through November 14, 1966. The Air Force Project Officers were Capt. Joel A. Tolson and Lt. James R. Noyce. The Rocket Research Corporation Program Manager was Dr. Donald R. Poole.

This report has been assigned a secondary report number RRC-66-R-74 by Rocket Research Corporation.

This report contains no classified information extracted from classified documents.

This technical report has been reviewed and approved.

W. H. Ebelke, Colonel, USAF
Chief, Propellant Division

ABSTRACT

The objective of this program was to characterize monopropellant hydrazine-based monopropellants which, by the use of ammonia and ammonia-water diluents, are capable of producing clean, low temperature gases when passed through a catalytic decomposition chamber. During the course of the p2-month program, thermochemical calculations were performed on a large number of cases involving various compositions of hydrazine, ammonia, and water. The effect of varying the amount of ammonia dissociation was investigated in the above calculations. Based upon the results of the thermochemical calculations and preliminary physical property testing, seven different solutions composed of various concentrations of hydrazine, water and/or ammonia were selected for further evaluation. The freezing points of the solutions were determined; and the vapor pressures, densities, and viscosities were measured over a wide temperature range. A low temperature gas generator was designed to produce approximately 60 standard cubic feet of gas per minute and to operate at a nominal chamber pressure of 300 psi. This gas generator was fired with each of the seven monopropellants in order to determine their steady state performance characteristics. In addition, a 1 lbf gas generator thruster was fired in pulse mode operation at various pulse widths and duty cycles with each of the seven monopropellants. The complete test results are presented in tabular form.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF TABLES

SECTION I

CONTRACT SCOPE

1.1 General

This program was conducted in three phases. Phase I involved conducting thermochemical calculations which provided theoretical data to assist in the selection of propellant systems for experimental evaluation. Phase II consisted of the determination of the physical properties of the selected propellants. Experimental delivered performance data was determined in Phase III.

This program was basically a propellant study and did not involve development of gas generator hardware, although a heavyweight experimental reactor was designed and fabricated for propellant evaluation purposes.

1.2 Thermochemical Calculations (Phase I)

Thermochemical calculations were performed on various compositions for the hydrazine-ammonia-water system. The effect of varying amounts of ammonia dissociation was investigated in addition to the effect of varying the chamber pressure.

1.3 Propellant Characterization (Phase II)

Seven different solutions composed of various concentrations of hydrazine, water and/or ammonia were selected for characterization studies. The selection of these propellants was based on the results of the thermochemical calculations and on preliminary physical property testing. The freezing point, density, vapor pressure and viscosity of each propellant was then measured.

1.4 Gas Generator Testing (Phase III)

A heavyweight experimental reactor was designed and fabricated. The reactor operated at a nominal chamber pressure of 250 psia and produced approximately 60 standard cubic feet of gas per minute. Each of the seven propellants was evaluated using this reactor.

SECTION II

THERMOCHEMICAL CALCULATIONS

2.1 Computer Program Description

The computer facilities of the Service Bureau Corporation, Palo Alto, California, were utilized for Phase I thermochemical equilibrium analyses. The NASA computational procedure was used for solution of the basic problem, as published in NASA Report No. 1037. The thermochemical data employed in this analysis was obtained from the joint Army, Navy, Air Force (JANAF) Interim Thermochemical Tables.

2.2 Chamber Conditions

The decomposition of hydrazine may be considered to take place according to the following consecutive reactions:

$$3N_2H_4 \rightarrow 4NH_3 + N_2 \tag{1}$$

$$2NH_3 \rightarrow N_2 + 3H_2 \tag{2}$$

For the purpose of calculating the relative amounts of the reactants, it was assumed that equation (1) goes to completion. The extent to which reaction (2) takes place is determined by the efficiency of the catalyst used and the design details of the reaction chamber.

Reactions (1) and (2) may be combined as follows:

$$N_2H_4 \rightarrow 4/3\,(1 - X)\,NH_3 + \left(\frac{2X + 1}{3}\right) N_2 + 2XH_2 \tag{3}$$

Where

X = fraction of NH_3 dissociated.

For the cases in which various concentrations of ammonia in hydrazine were considered, X represents only the fraction dissociation of the ammonia which was derived from the decomposing hydrazine, and Y represents the fraction of the added ammonia which has dissociated.

The input compositions were calculated in units of gram-atoms per 100 grams of reactant for hydrogen, oxygen, and nitrogen and gram-moles per 100 grams of reactant for ammonia by means of the following equations:

$$\frac{4(1-X)}{3}\left(\frac{P_h}{32.048}\right) + (1-Y)\left(\frac{P_{am}}{17.032}\right) = (NH_3) \quad (4)$$

$$\frac{2(1-X)}{3}\left(\frac{P_h}{32.048}\right) + Y\left(\frac{P_{am}}{17.032}\right) = (N) \quad (5)$$

$$\frac{2P_w}{18.016} + \frac{4P_hX}{32.048} + \frac{3P_{am}Y}{17.032} = (H) \quad (6)$$

$$\frac{P_w}{18.016} = (0) \quad (7)$$

Where:

P_h = weight percent hydrazine in reactants

P_{am} = weight percent ammonia in reactants

P_w = weight percent water in reactants

X = fraction ammonia (derived from hydrazine) dissociated

Y = fraction of added ammonia dissociated

Calculations were performed for numerous propellant compositions where arbitrary amounts of ammonia were impressed upon the reaction products in the chamber. In these cases, ammonia was not allowed to dissociate and the formation of additional ammonia was not permitted. For practical purposes this condition specified the composition of the chamber gases for these reactants. Numerous calculations were also performed in which complete chemical equilibrium was allowed to exist. Equilibrium conditions were applied whenever X = Y = 1.

All calculations were carried out under frozen flow conditions. Calculations under shifting flow conditions were not necessary since the results would be identical to frozen flow conditions for all practical purposes.

2.3 Thermochemical Data

The heats of formation used in the thermochemical calculations are listed in Table I. These values were derived from the standard heat of formation of each component of the solutions and the heats of solution of ammonia and water in hydrazine.

TABLE I

HEAT OF FORMATION OF HYDRAZINE SOLUTIONS

Weight % N_2H_4	Weight % NH_3	Weight % H_2O	ΔH kcals/100 gm
100	0	0	+ 37.5998
90	0	10	- 5.5018
70	0	30	- 90.7060
65	0	35	-111.4167
60	0	40	-132.9876
55	0	45	-153.5183
50	0	50	-174.4393
45	0	55	-195.3601
40	0	60	-216.2509
30	0	70	-258.0026
95	5	0	+ 30.399
90	10	0	+ 24.508
80	20	0	+ 11.486
70	30	0	- 1.552
60	40	0	- 14.558
55	45	0	- 21.069
50	50	0	- 27.580
40	60	0	- 40.602
35	65	0	- 47.113
30	70	0	- 53.624
80	10	10	- 18.691

Values of the heat of solution for various concentrations of ammonia in hydrazine were obtained from the data given in Reference 1. After conversion to the appropriate units, this information was plotted as shown in Figure 1. This graph indicates that the heat of solution is essentially constant for concentrations greater than about 5%. The value -0.07 kcal/100 g was therefore applied as a correction in all cases involving ammonia solutions, even though a correction of this magnitude has very little influence on the results.

Corrections for the heat of solution for the various concentrations of water in hydrazine were obtained from Figure 2 (References 2 and 3).

For those solutions containing both ammonia and water in hydrazine, the heats of solution were estimated from values for the two component systems. The constant value of -0.07 kcal/100 g was applied to correct for the heat of solution of ammonia in hydrazine. The concentration of water in hydrazine was calculated as though no ammonia was in the solution and the corresponding heat of solution was then obtained from Figure 2.

Thermochemical calculations were performed on a test case in an effort to determine the significance of the heat of solution corrections. The test case consisted of 30% ammonia and 70% hydrazine with X = .4 and Y = 0 and was calculated both with and without the heat of solution correction. When the correction was applied, the chamber temperature was 931.08°K and the characteristic exhaust velocity was 3,559 ft/sec. Without the correction, these values were 932.11°K and 3,561 ft/sec. From these values it was concluded that any errors which may have been introduced by the described methods of correcting for the heat of solution would not influence the results significantly.

2.4 Discussion of Results

The results of the Phase I thermochemical calculations are summarized in Tables II, III, and IV and in Figures 4 through 15 respectively, in the Appendix. These figures illustrate the wide ranges of chamber temperatures and performance which are theoretically possible through the use of mixtures of ammonia, water, and hydrazine.

During a later phase of the program, after the selection of the propellant compositions which were characterized and tested in the reactor, another series of calculations was performed. These calculations, summarized in Table V, provide a more direct comparison with the results of the reactor testing (Phase III) than was possible with the

HEAT OF SOLUTION

AMMONIA - HYDRAZINE SOLUTIONS

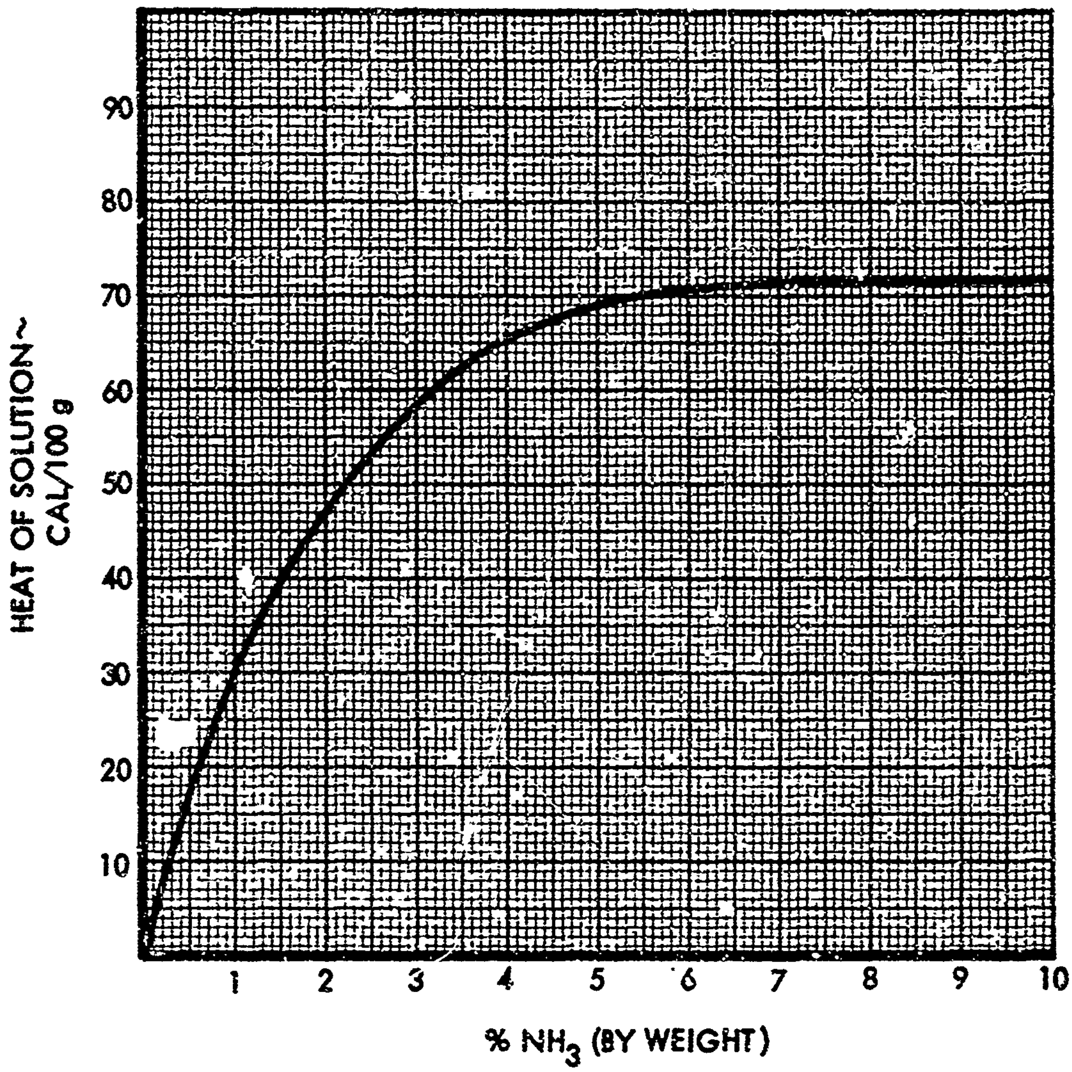


FIGURE 1

HEAT OF SOLUTION
WATER - HYDRAZINE SOLUTIONS

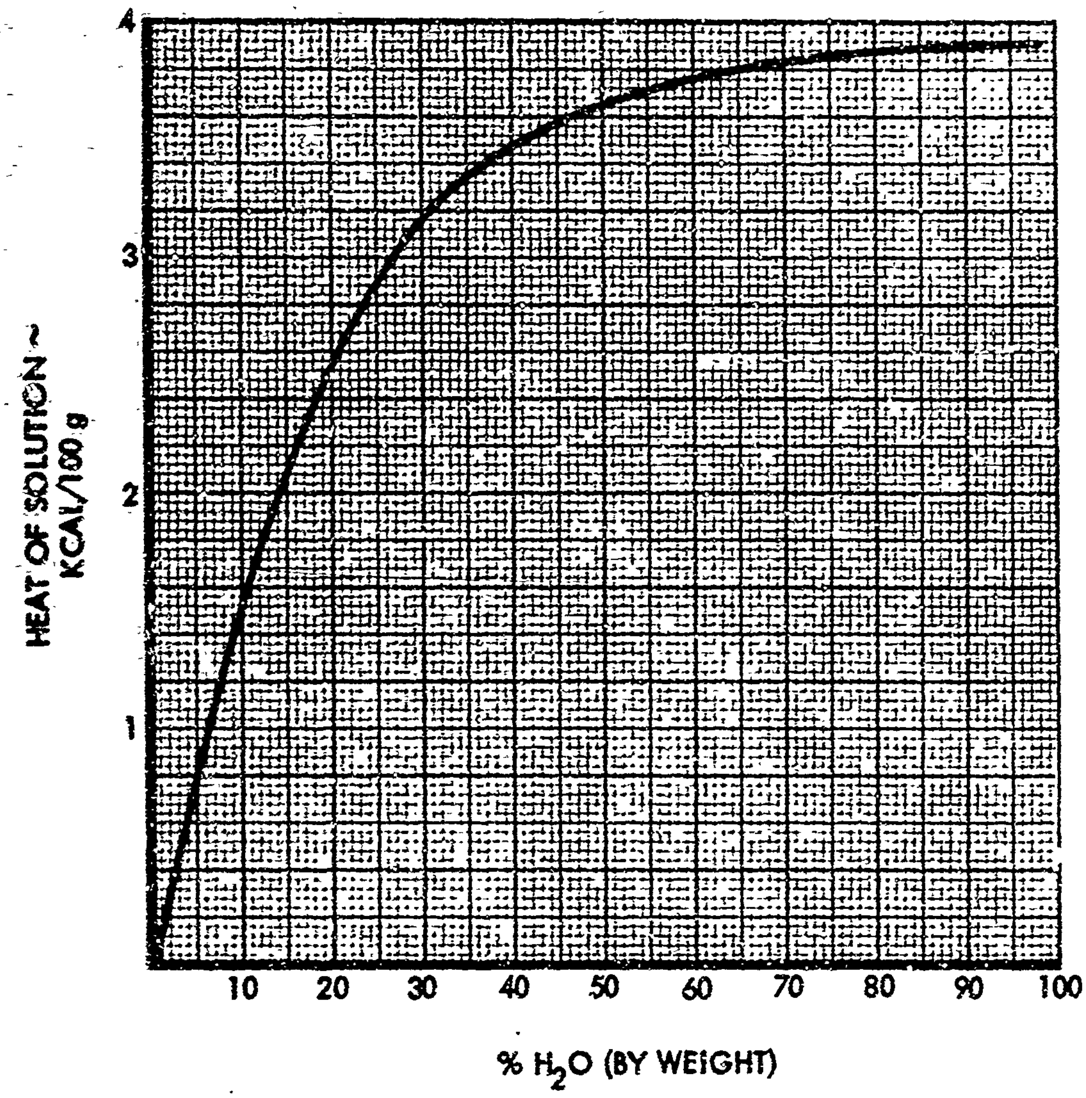


FIGURE 2

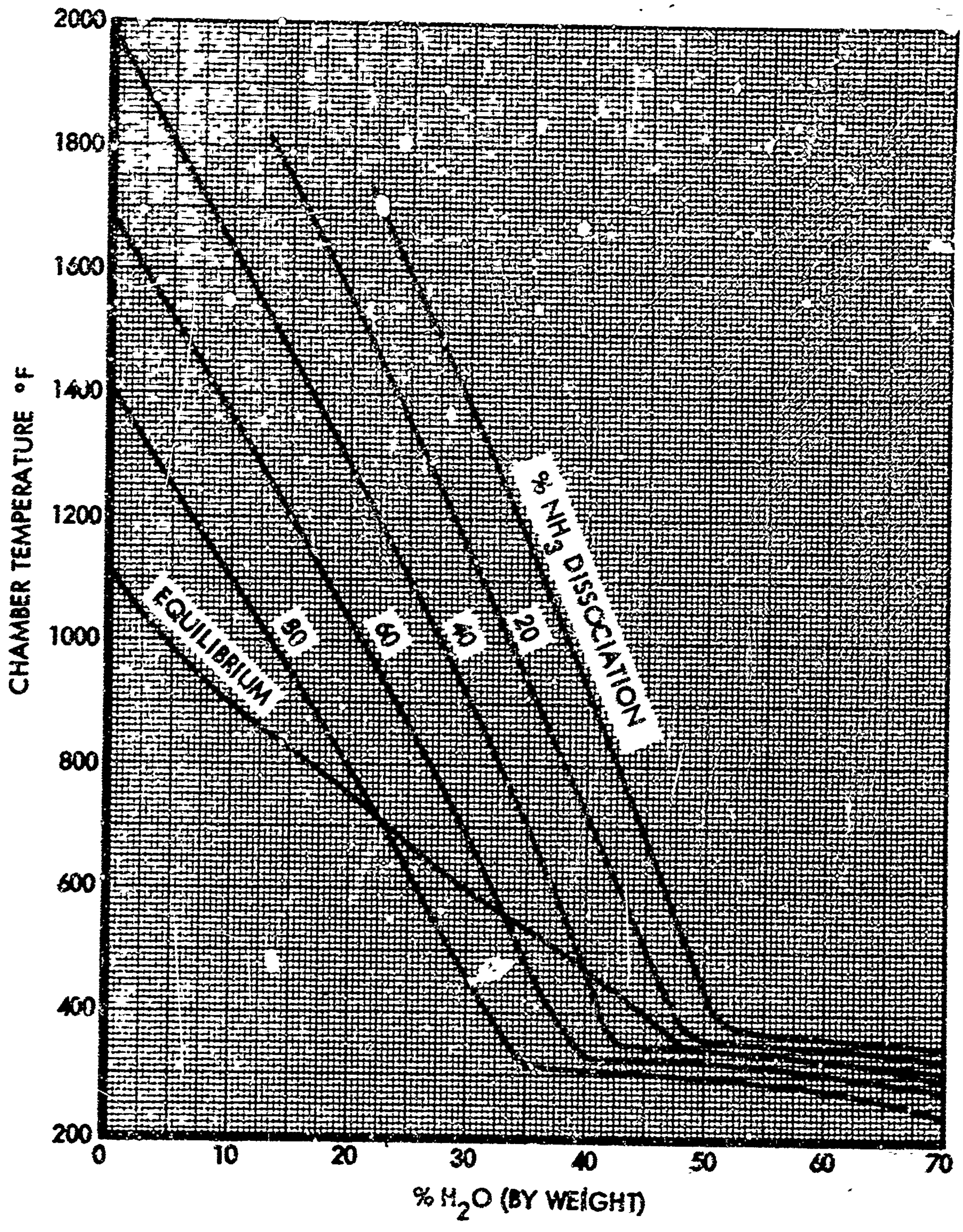
TABLE V
THEORETICAL PERFORMANCE
SELECTED HYDRAZINE-AMMONIA-WATER SYSTEMS
CHAMBER PRESSURE = 300 psia – EXHAUST PRESSURE = 14.7 psia

ΔH° Kcal/100g	Code No.	% N_2H_4	% NH_3	% H_2O	X	Y	T_c ~ °K	T_c ~ °F	c^* ft/sec	I_{sp} sec	ΔH_R Kcal/100gm	M.W.	Frozen Gamma (Ch.)	Moles H_2	Moles N_2	Moles NH_3	Moles H_2O (Gas)	Moles H_2O (Liquid)
-93,520	3.307.00	69.3	--	30.7	0.0	--	1012	1362	3364	146.45	-24,469	18.839	1.2101	--	0.7208	2.8832	1.7040	--
-93,520	3.307.20	69.3	--	30.7	0.2	--	885	1133	3281	141.88	-22,965	16.945	1.2463	0.8650	0.9832	2.3035	1.7040	--
-93,520	3.307.40	69.3	--	30.7	0.4	--	756	901	3150	135.46	-20,782	15.373	1.2860	1.7300	1.2456	1.7299	1.7040	--
-170,261	3.49.00	51	--	49	0.0	--	527	489	2384	105.80	-12,864	18.615	1.2940	--	0.5305	2.1218	2.7198	--
-216,251	3.60.00	40	--	60	0.0	--	456	361	1996	88.4	- 8,990	18.482	1.154	--	0.416	1.664	1.918	1.413
-216,251	3.60.20	40	--	60	0.2	--	447	344	1978	87.9	- 8,885	17.411	1.139	0.499	0.582	1.331	1.554	1.776
-216,251	3.60.40	40	--	60	0.4	--	436	325	1957	87.2	- 8,744	16.458	1.127	0.999	0.749	0.998	1.202	2.128
-53,624	4.70.00	30	70	--	0.0	--	410	278	2173	93.8	-10,122	17.636	1.232	--	0.312	5.358	--	--
-53,624	4.70.20	30	70	--	0.2	--	355	179	2062	88.7	- 9,033	16.893	1.283	0.374	0.437	5.108	--	--
-53,624	4.70.40	30	70	--	0.4	--	302	084	1922	82.9	- 7,892	16.209	1.320	0.749	0.562	4.859	--	--
-86,346	7.2625.875.00	65	26.25	8.75	0.0	--	944	1240	3260	141.80	-23,109	18.680	1.2118	--	0.6761	3.2180	1.4570	--
-86,346	7.2625.875.20	65	26.25	8.75	0.2	--	824	1024	3162	136.67	-21,467	16.972	1.2472	0.8114	0.9465	2.6771	1.4570	--
-86,346	7.2625.875.40	65	26.25	8.75	0.4	--	704	808	3021	129.93	-19,403	15.545	1.2862	1.6228	1.2169	2.1363	1.4570	--
-116,295	7.275.275.00	45	27.5	27.5	0.0	--	518	473	2395	105.65	-12,828	18.244	1.2823	--	0.4681	3.4868	1.5264	--
-116,295	7.275.275.20	45	27.5	27.5	0.2	--	418	293	2132	94.74	-15,184	19.522	1.3109	0.5617	2.3402	3.1121	1.4363	0.1001
-143,861	7.325.325.00	35	32.5	32.5	0.0	--	419	294	2064	92.14	- 9.756	18.076	1.1945	--	0.3640	3.3643	0.9252	0.8787

previous calculations. It is interesting to note the abrupt changes in the slopes of the curves in Figures 3 and 3a. These changes are assumed to be due to the (theoretical) condensation of water in the chamber.

HYDRAZINE - WATER SYSTEM

CHAMBER TEMPERATURE VS % H_2O
FOR VARIOUS AMMONIA DISSOCIATION



HYDRAZINE - WATER SYSTEM

CHAMBER TEMPERATURE VS % H_2O
FOR VARIOUS AMMONIA DISSOCIATION

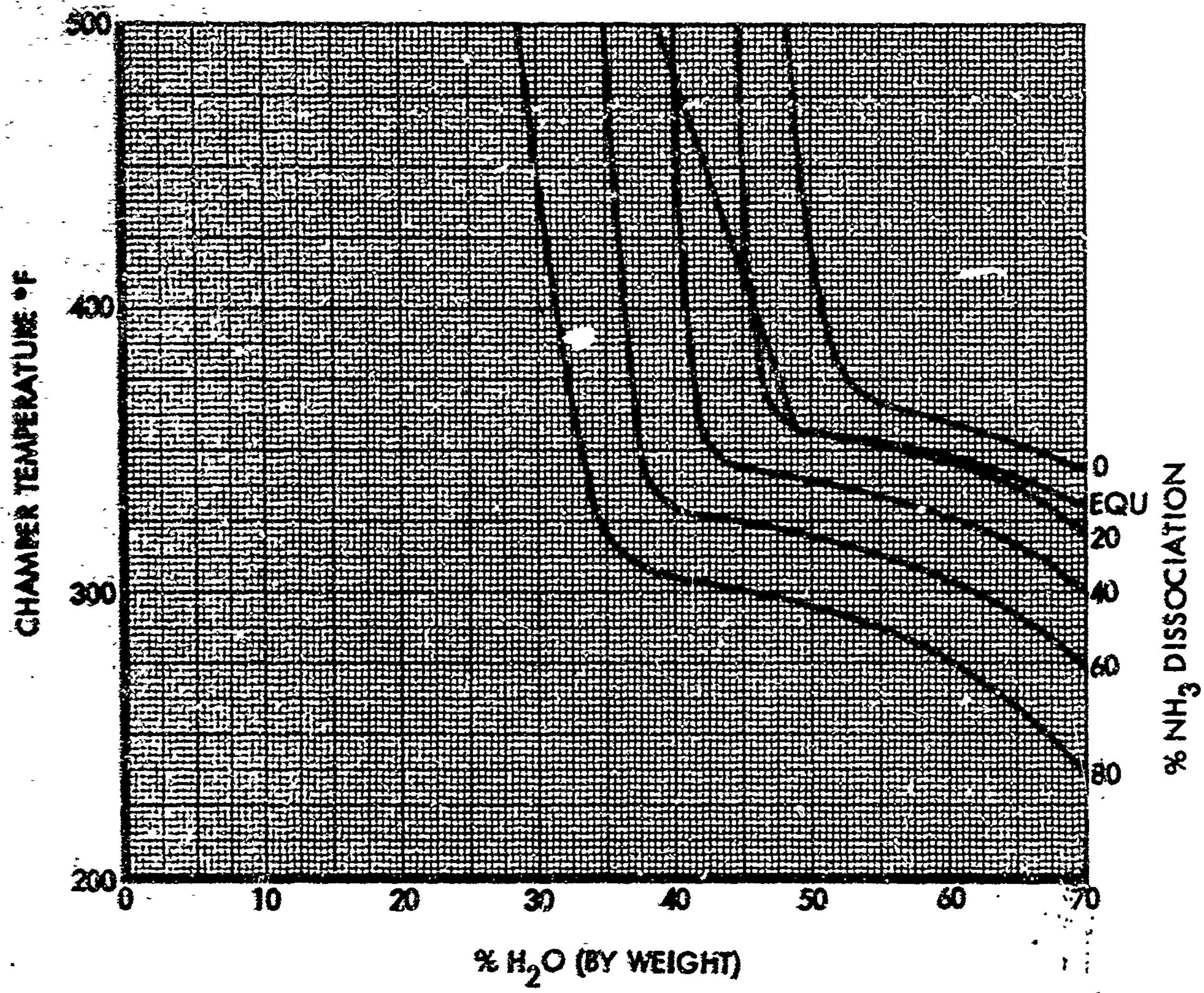


FIGURE 3c

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SECTION III

PROPELLANT CHARACTERIZATION

3.1 Preliminary Evaluation

Preliminary testing was conducted to generate information required in the selection of solutions for further study.

Solutions with various concentrations of hydrazine, ammonia and water were sealed in heavy-wall, glass tubing and the freezing points of the solutions were determined. The compositions and freezing points of these solutions are listed in Table VI. Figure 16 illustrates this information and includes the freezing point curve for the hydrazine-water system taken from the work of Hill and Sumner (Reference 4).

It is interesting to note that solutions having a water to ammonia ratio (by weight) larger than one have lower freezing points than solutions containing only water and hydrazine at the same percent additive. Solution GT-5 would not freeze at -110°F although it was packed in dry ice overnight. This solution was also cooled in liquid nitrogen, but a glass-like material resulted and no freezing point was observed.

Although it was considered unlikely that any phase separation would occur, the samples numbered GT-1 through 5, 8, and 11, which were used for the freezing point determinations, were placed in individual lucite tubes and then placed in a temperature-controlled oven. The door of the oven was replaced by a lucite plate, and the temperature was increased in small increments up to 160°F. Each temperature was held constant for at least one-half hour, and the samples were held at 160°F overnight. A light was placed behind the samples to facilitate viewing. The samples were observed visually, and no evidence (such as opalescence or a second liquid layer) of the appearance of a second liquid phase was observed.

It may be concluded, therefore, that hydrazine, ammonia, and water are completely miscible at temperatures from the freezing point up to 160°F and over the concentration range of interest for this study.

The vapor pressure of two hydrazine, water, and ammonia solutions was measured at various temperatures. This information is illustrated in Figures 17 and 18.

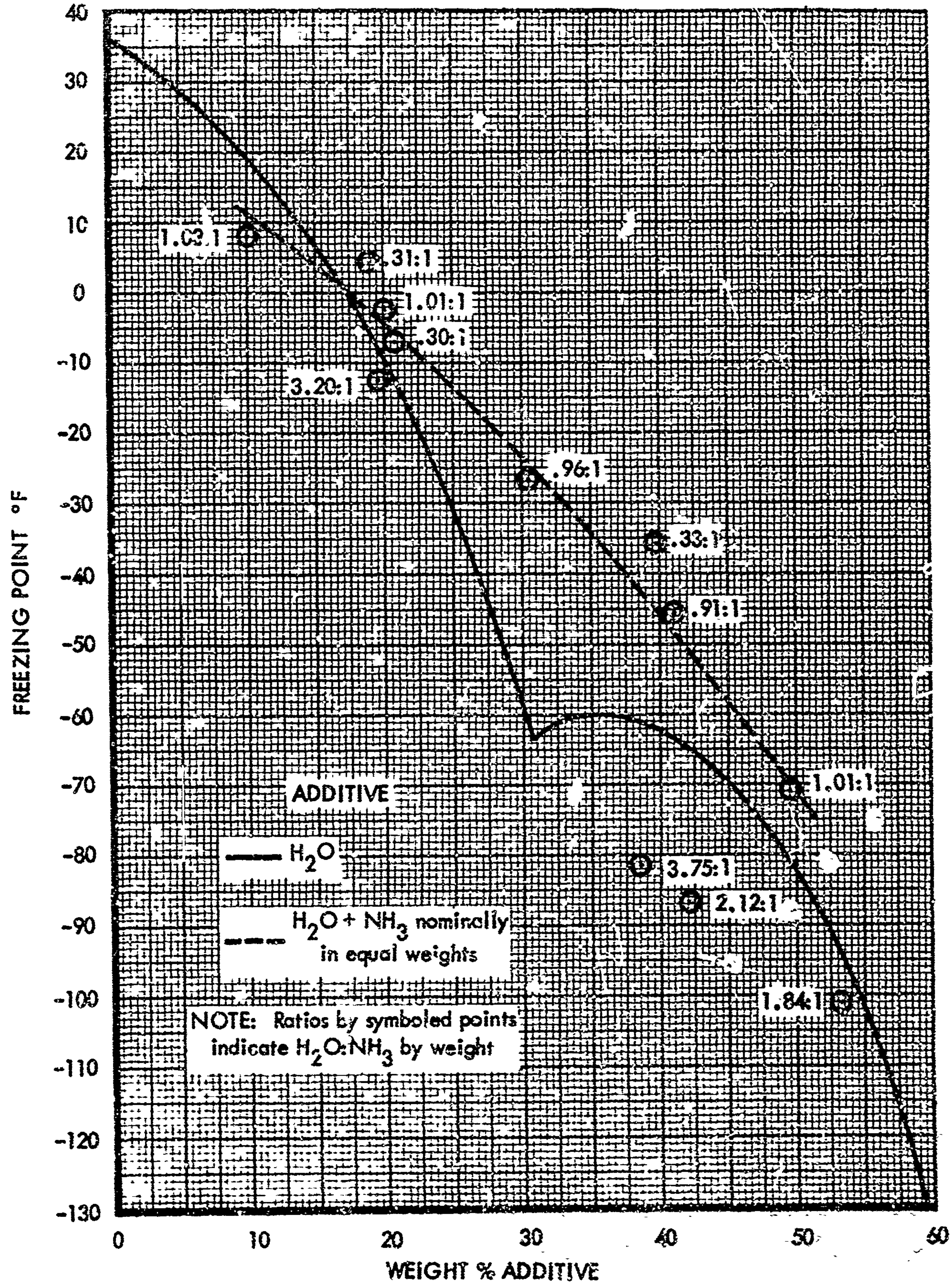
The methods used for these measurements is described in Paragraph 3.3.

TABLE VI

COMPOSITION AND FREEZING POINTS OF HYDRAZINE-AMMONIA-WATER SOLUTIONS

Solution Designation	Weight Percent			Freezing Point °F
	H_2O	NH_3	N_2H_4	
GT-1	4.51	14.34	81.15	+4
GT-2	30.50	8.14	61.36	-82
GT-3	19.62	21.50	58.87	-46
GT-4	14.92	15.47	69.61	-27
GT-5	30.55	28.71	40.74	<-110
GT-6	5.03	4.87	90.10	+8
GT-7	10.01	9.92	80.07	-3
GT-8	25.08	24.76	50.16	-71
GT-9	34.70	18.82	46.48	-101
GT-10	28.71	13.53	57.76	-87
GT-11	4.78	15.97	79.25	-7
GT-12	14.89	4.66	80.45	-13
GT-13	9.88	29.96	60.16	-36

FREEZING POINT VS WEIGHT % ADDITIVE FOR VARIOUS N_2H_4 SOLUTIONS



VAPOR PRESSURE VS. TEMPERATURE
29.89% H_2O, 30.07% NH_3, 40.04% N_2H_4

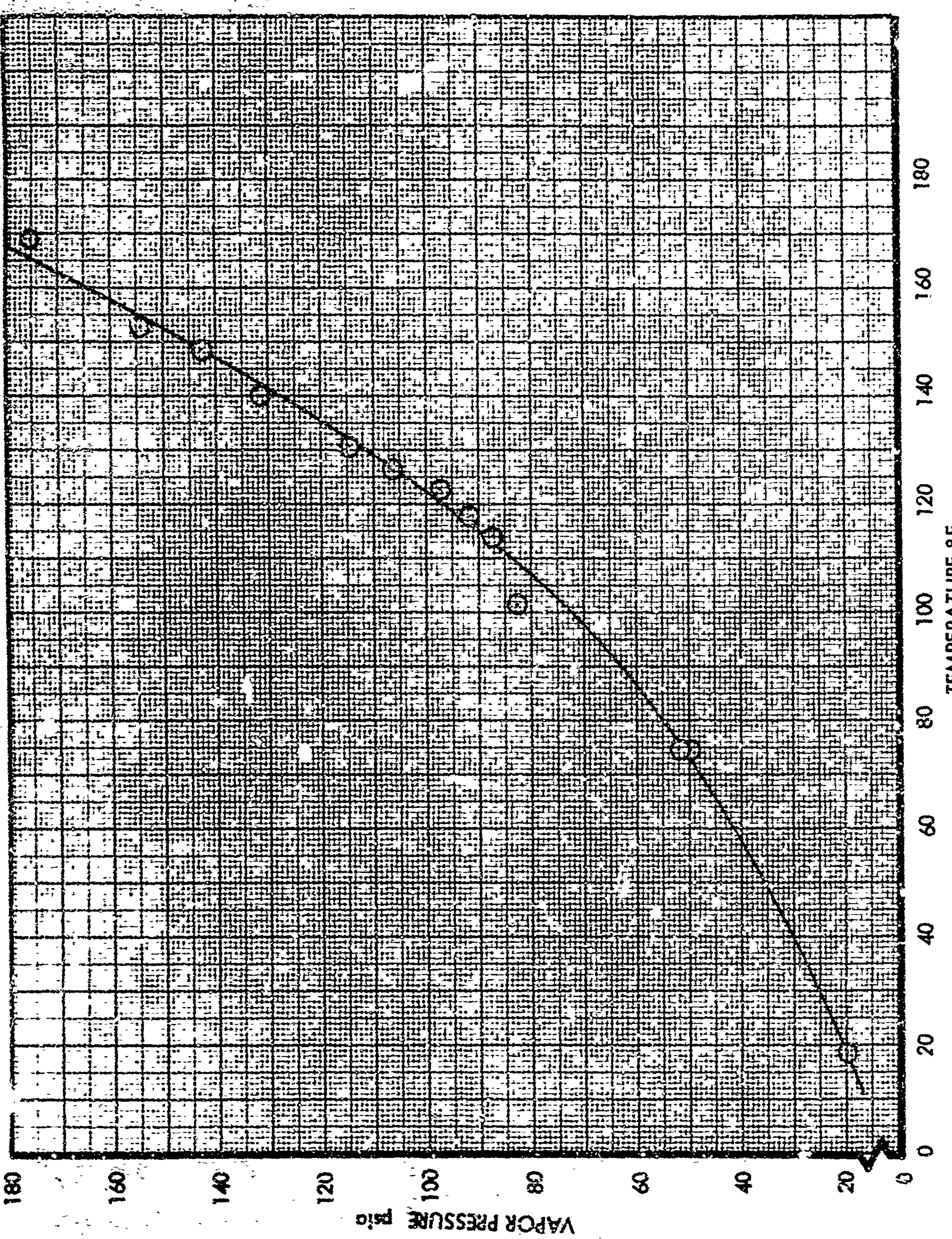


FIGURE 17

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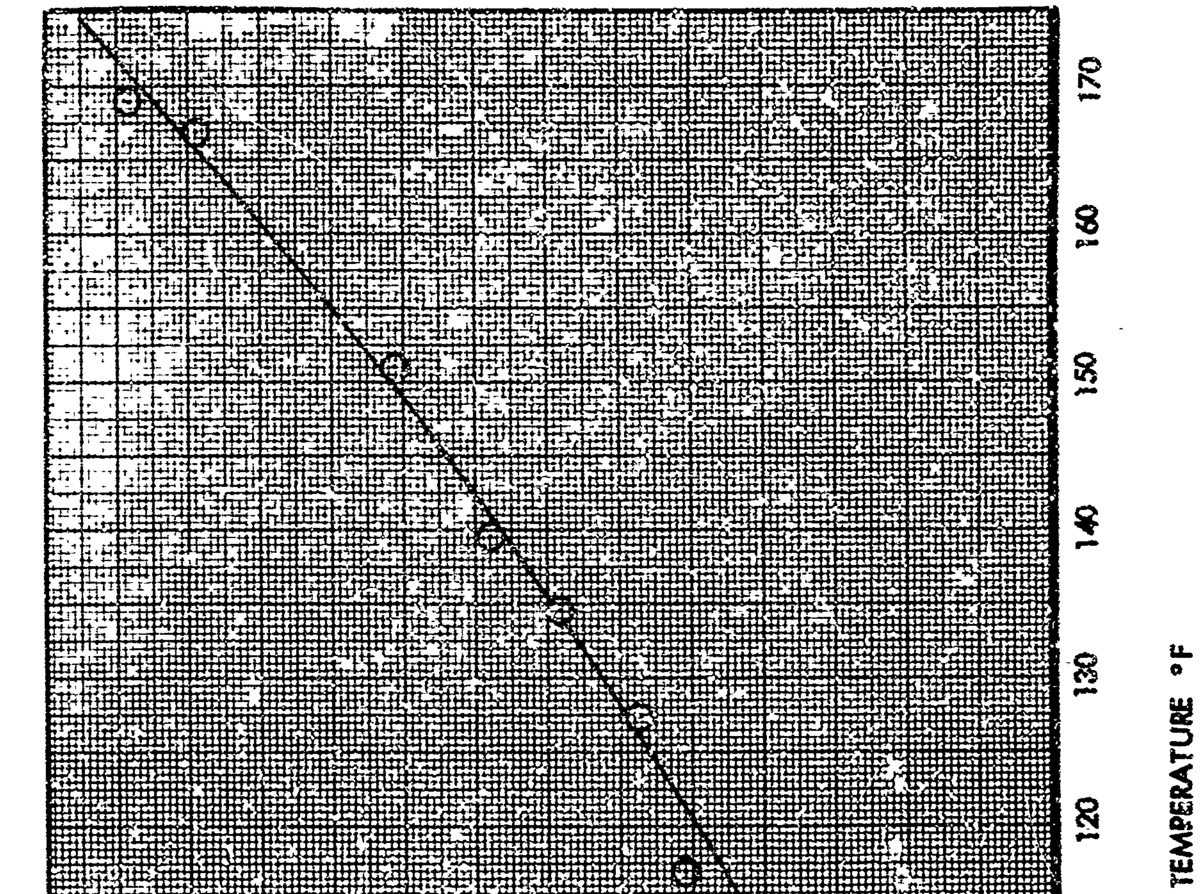
VAPOR PRESSURE VS TEMPERATURE

$60.06\%\ H_2O,\ 9.87\%\ NH_3,\ 30.07\%\ N_2H_4$



3.2 Selection of Propellants

After consideration of the thermochemical calculations and the information described in Paragraph 3.1, seven low temperature gas generator propellants were selected for further evaluation. The physical properties of these propellants were measured as a function of temperature, and their performance was determined in reactor firings.

The compositions of the solutions were chosen in order to provide estimated chamber temperatures over the range of 275°F to 925°F, to have low freezing points, and to provide data on a variety of propellant compositions. The compositions, estimated chamber temperatures, and measured freezing points are listed in Table VII.

3.3 Physical Properties Determinations

3.3.1 Preparation of Propellants

Anhydrous hydrazine obtained from Olin Chemicals was analyzed by the J. M. Kniseley Engineering Company, Seattle, Washington, and the results of the analysis were utilized in calculating the concentration of water in the solutions which were mixed.

Ammonia, obtained from the J. T. Baker Chemical Company and specified as 99.99% ammonia, was used as received.

For the preparation of solutions to be used for freezing point determination, glass tubes approximately 10 inches long were prepared from tubing having an inside diameter of 8 mm and a wall thickness of 1.5 mm. The tubes were sealed on one end and a constriction was placed approximately two inches from the open end by heating the tube until the walls softened and collapsed, leaving a passageway of approximately 2 mm.

After weighing the empty glass tube on an analytical balance, the appropriate amount of hydrazine-water solution was placed in the lower part of the tube by means of a micropipet and the tube was then reweighed. The tube was then attached to the vacuum manifold by means of a short rubber vacuum tube. The hydrazine water solution was frozen by immersing the tube in liquid nitrogen and the tube was evacuated. Ammonia was then metered into the vacuum manifold to slightly less than atmospheric pressure as indicated by a mercury manometer. The vacuum manifold has two, one-liter flasks attached by stopcocks so that either one, or both, flasks

TABLE VII

COMPOSITIONS OF SELECTED LOW TEMPERATURE GAS GENERATOR PROPELLANTS

Solution No.	Composition % by Weight			Estimated Chamber Temp. °F	Measured Freezing Point °F
	N_2H_4	H_2O	NH_3		
LT-1	69.3	30.7	---	925	-64
LT-2	45	27.5	27.5	500	-80
LT-3	35	32.5	32.5	275	-104
LT-4	40	60	---	350	-130
LT-5	51	49	---	500	-80
LT-6	30	---	70	300	-75
LT-7	65	26.25	8.75	900	-57

can be included in the volume of the manifold. The manifold volume was calibrated by absorbing ammonia in water and noting the increase in weight of the solution and the decrease in pressure within the manifold. The pressure change required to deliver the desired amount of ammonia was calculated, and the ammonia was then condensed into the glass tube by cooling with liquid nitrogen. The tube was then sealed off, and both parts were weighed after the tube warmed to room temperature. The actual amount of ammonia in the solution was, therefore, determined by weight.

Solutions which were mixed in larger quantities for vapor pressure, viscosity, and density measurements were prepared in stainless steel cylinders. The hydrazine-water solution was drawn into an evacuated, weighed cylinder which was then re-weighed to determine the exact amount of solution. lightly more than the calculated amount of ammonia required for the solution was then condensed into a separate cylinder. The exact weight of ammonia was then adjusted, after warming to room temperature, by alternately bleeding off ammonia and weighing the cylinder. The weighings were performed on a Mettler precision top-loading scale capable of weighing to $\pm$ 0.02 gm. The hydrazine-water solution was then frozen in liquid nitrogen and the ammonia was condensed into the solution cylinder. After warming to room temperature, the solution was mixed by vigorous shaking.

3.3.2 Freezing Point Determinations

The freezing points of the solutions containing ammonia were determined by the technique described below.

An acetone cold-bath was prepared in a large, clear-glass Dewar flask. A spark-proof stirrer provided the agitation necessary to keep an even temperature throughout the bath. The sample tube was handled by means of a small apparatus clamp with vinyl fingers. The sample was partly frozen by immersing in a separate dry ice bath and then was completely immersed in the large cold-bath. The tube was then rocked back and forth by hand and the crystals were viewed, with the aid of a strong light, through the walls of the clear Dewar flask. If the crystals melted, the bath was cooled by adding dry ice and the process was repeated. If the solution continued to freeze, the bath was warmed slightly by a small immersion heater. The freezing point was thus bracketed, and the process was repeated until the freezing point was determined as accurately as required. The freezing point is defined as the temperature at which

the last solid disappears upon slowly warming the solution. Due to the large volume of the acetone bath (approximately four gallons) the temperature changes very slowly when adding dry ice or heating and it is possible to control the temperature easily to a small range. The accuracy of freezing points determined by this method is believed to be about $\pm$ 0.5°F for temperatures down to about -60°F and about $\pm$ 1.0°F for lower temperatures. All thermometers used in these tests were certified to conform to ASTM Standards.

The solutions containing 27.5 and 32.5 per cent ammonia exhibited a marked tendency to supercool and considerable difficulty was experienced in freezing the solutions. Crystallization of both solutions was accomplished, however, and the freezing points were obtained by observing the disappearance of the last crystals upon slowly warming the solutions.

Freezing points of the solutions containing only hydrazine and water were taken from the data of Hill and Sumner (Reference 4). A part of their data was plotted on an expanded scale as shown in Figure 19, and the freezing points were taken from this graph.

3.3.3 Vapor Pressure Measurements

The vapor pressures of the solutions containing only hydrazine and water were measured in an all-glass apparatus consisting of a glass bulb, which holds the solution, connected to a short mercury manometer. The mercury was degassed by heating with a hand torch while evacuating the system. The solution was then added to the bulb and degassed by a freeze-evacuate-thaw-procedure which was repeated three times; the apparatus was then sealed while being evacuated. The complete apparatus was then immersed in a controlled temperature bath, and the mercury level was read by means of a cathetometer. The results of these measurements are shown in Figures 20 and 21.

The vapor pressures of the solutions containing ammonia were measured by means of a 0-300 psi, temperature compensated, Heise pressure gauge. The stainless steel cylinder containing the solution was connected to the pressure gauge through a 0.25 inch stainless tube and tee. The other end of the tee was closed by a small valve through which the apparatus, except for the cylinder, was evacuated. For temperatures below ambient, the cylinder was immersed in a cold bath and, at

FREEZING POINT VS WEIGHT % H_2O
FOR $N_2H_4 + H_2O$ SOLUTIONS

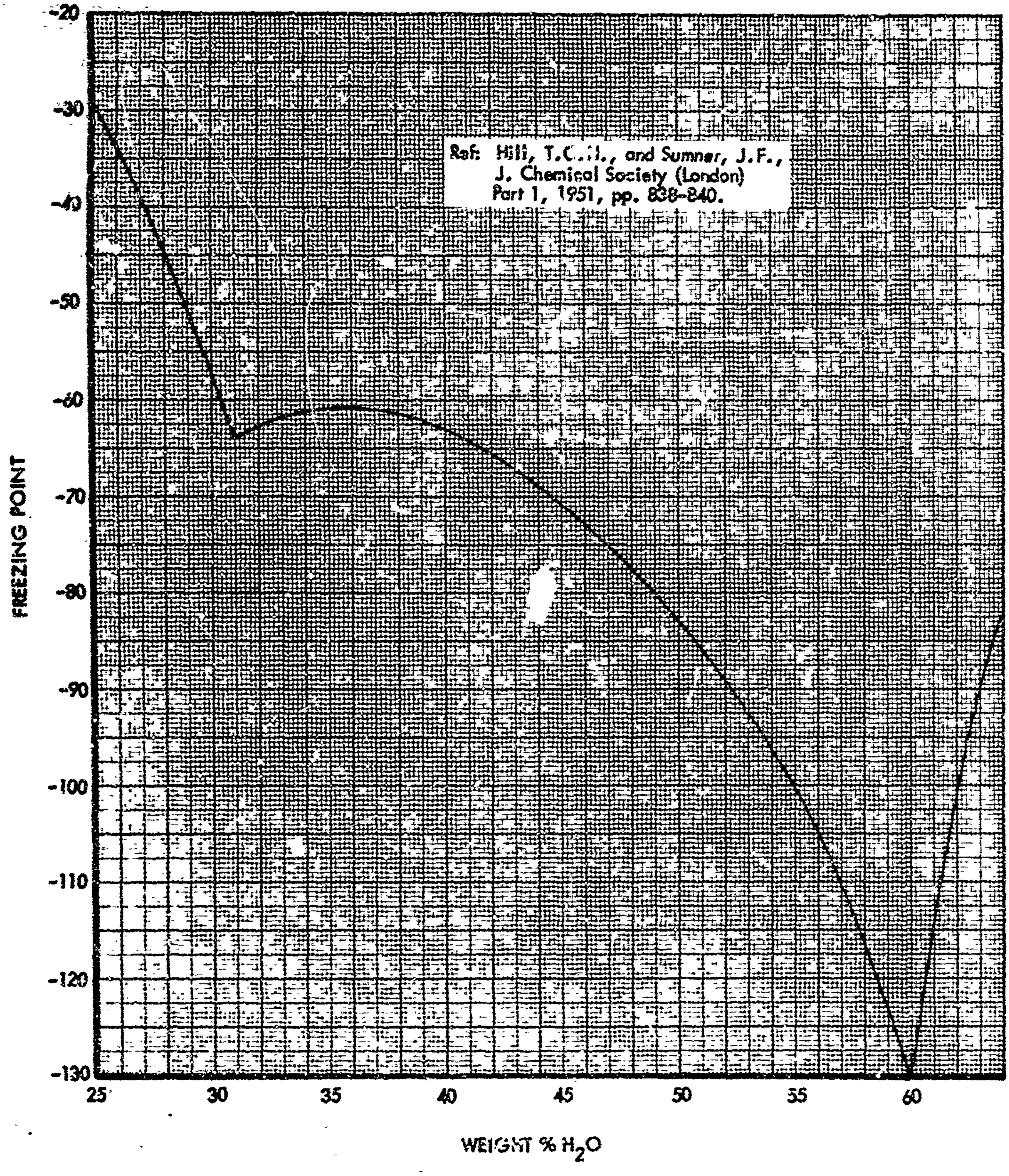
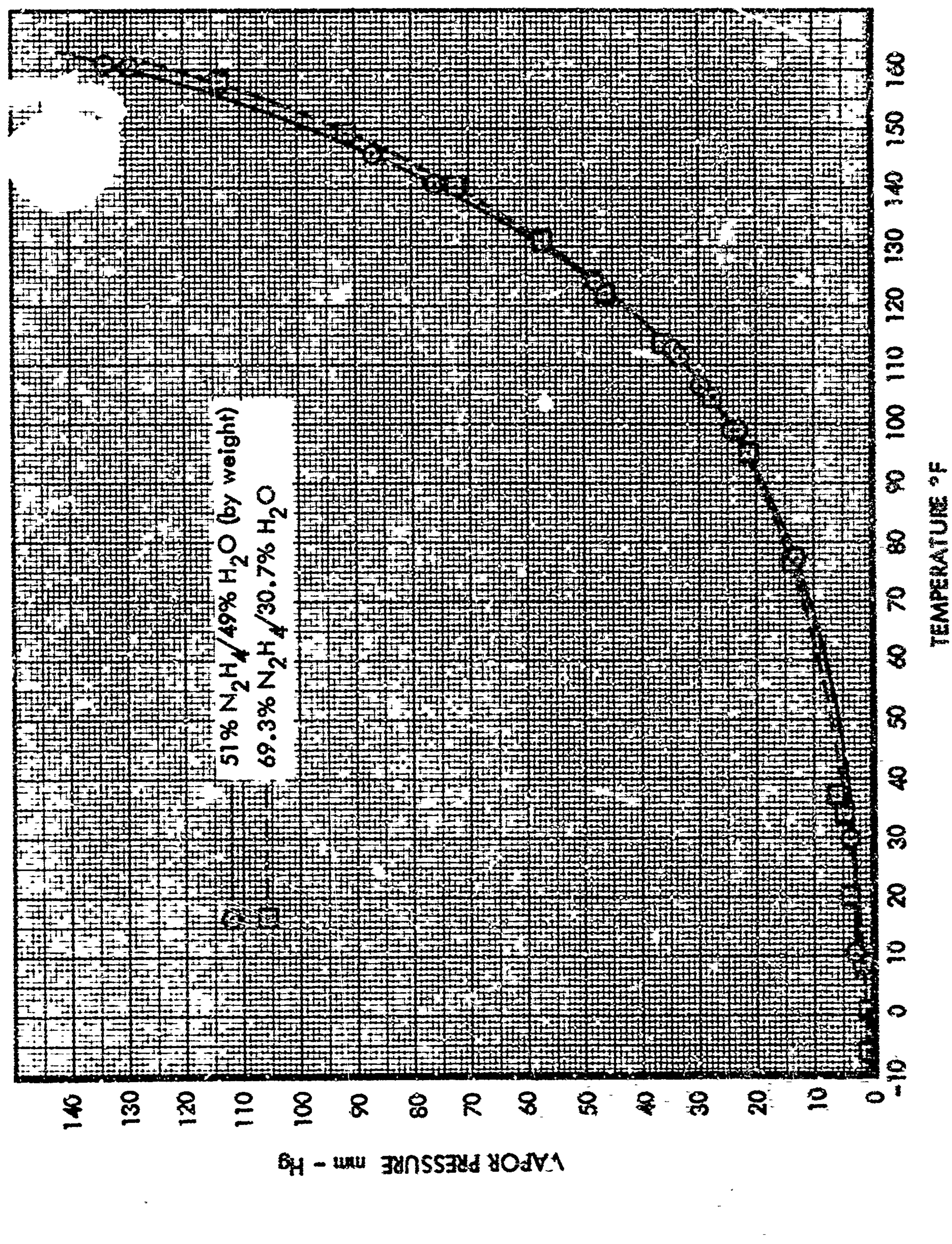


FIGURE 19

TEMPERATURE EFFECT ON VAPOR PRESSURE OF $N_2H_4 + H_2O$ SOLUTIONS



TEMPERATURE EFFECT ON VAPOR PRESSURE OF 40% N_2H_4/60% H_2O

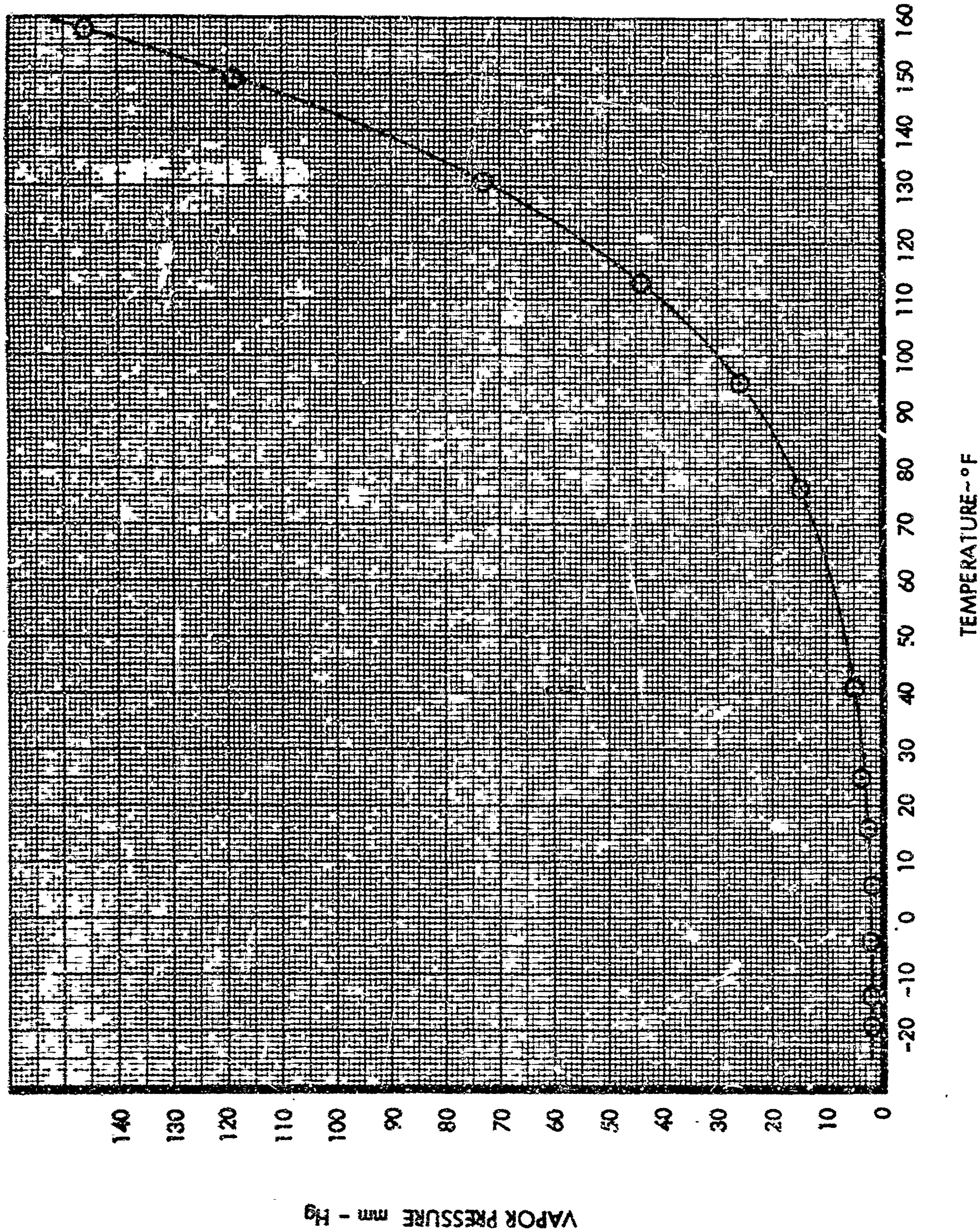


FIGURE 21

each temperature, was shaken until the pressure remained constant. For temperatures above ambient, the cylinder and pressure gauge were placed in a temperature controlled oven which is capable of maintaining the temperature constant to within $\pm$ 1°C. The temperature was increased in increments and was held constant at each temperature until the pressure remained constant for at least 15 minutes. The vapor pressures of the solutions containing ammonia are illustrated in Figures 22 and 23.

3.3.4 Viscosity Measurements

Viscosity measurements were performed on solutions containing only hydrazine and water by using Cannon-Fenske glass capillary viscometers. The measurements were conducted according to ASTM Standard Test Method D445-64-IP71. The viscometers were calibrated by the Cannon Instrument Company, State College, Pennsylvania.

The above method is not adequate for measuring the viscosity of solutions containing ammonia because of the higher vapor pressures which necessitated devising a new technique for these measurements. The apparatus, shown schematically in Figure 24, is an adaptation of the conventional rolling-ball viscometer. The viscometer consists, essentially, of a heavy-wall glass capillary tube with a small steel sphere which rolls down the inclined tube. The sphere is pulled to the top of the tube by means of a small magnet and then released. The time of travel of the sphere between two marks on the tube is measured by a stopwatch. The tube is held at a reproducible angle by a special clamp. This viscometer was calibrated with distilled water and a standard oil obtained from the Cannon Instrument Company.

The viscometer is loaded by a gravity flow arrangement shown schematically in Figure 25. The viscosities of the various solutions are illustrated in Figures 26, 27, and 28.

3.3.5 Density Measurements

Density measurements were run on the solutions containing only hydrazine and water by using the Lipkin Bicapillary pycnometer as specified in ASTM Standard Test Method D941-55. This method is not adequate for the solutions containing ammonia due to the higher vapor pressures and another technique was used.

A new pycnometer was fabricated which is similar to the Lipkin Bicapillary pycnometer except that heavy-wall glass capillary tubing was used and the ends of

TEMPERATURE EFFECT ON VAPOR PRESSURE
OF 65.0% N_2H_4, 26.25% H_2O, 8.75% NH_3

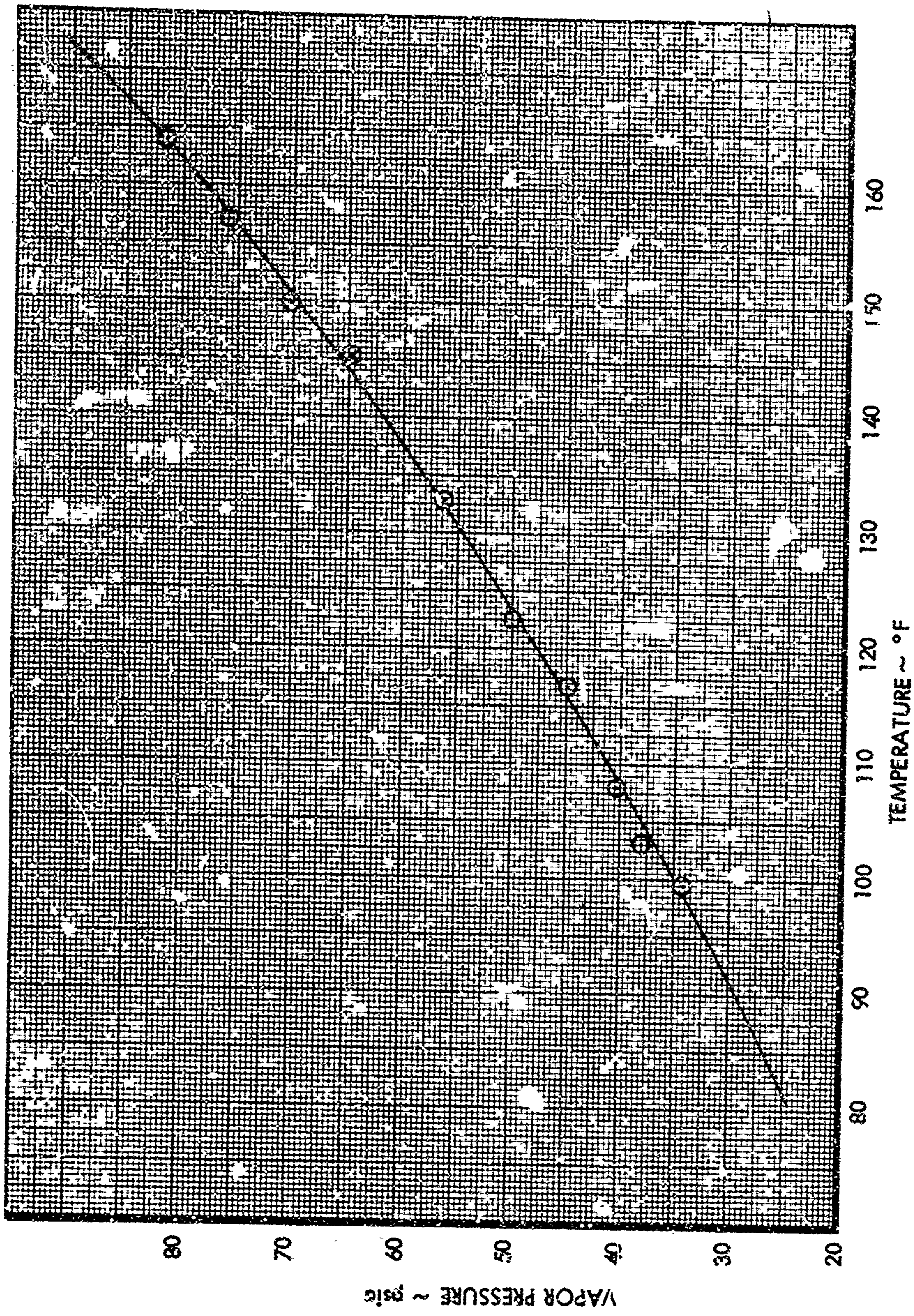
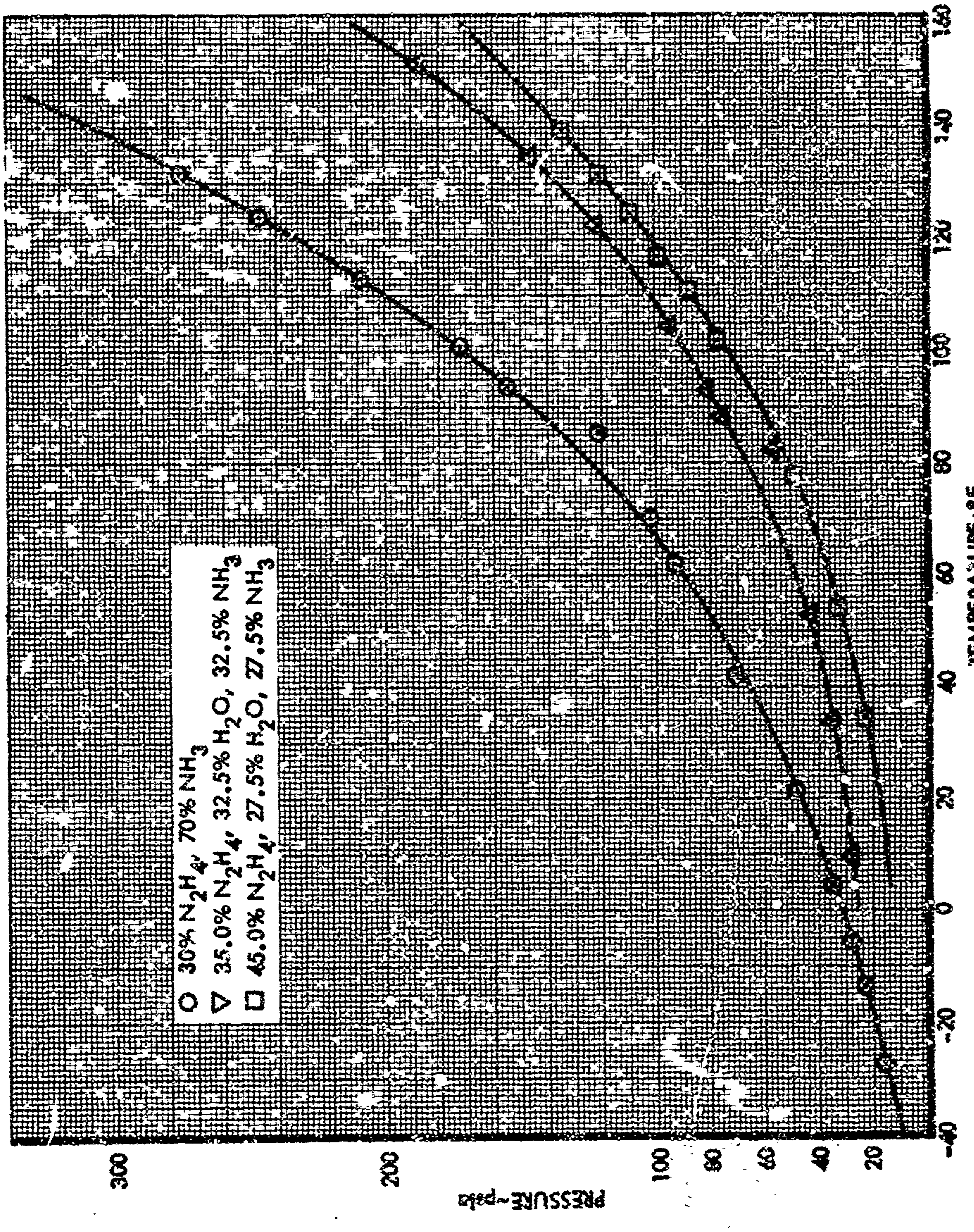


FIGURE 22

22043

TEMPERATURE EFFECT ON VAPOR PRESSURE
OF HYDRAZINE - AMMONIA - WATER SOLUTIONS



ROLLING BALL VISCOMETER

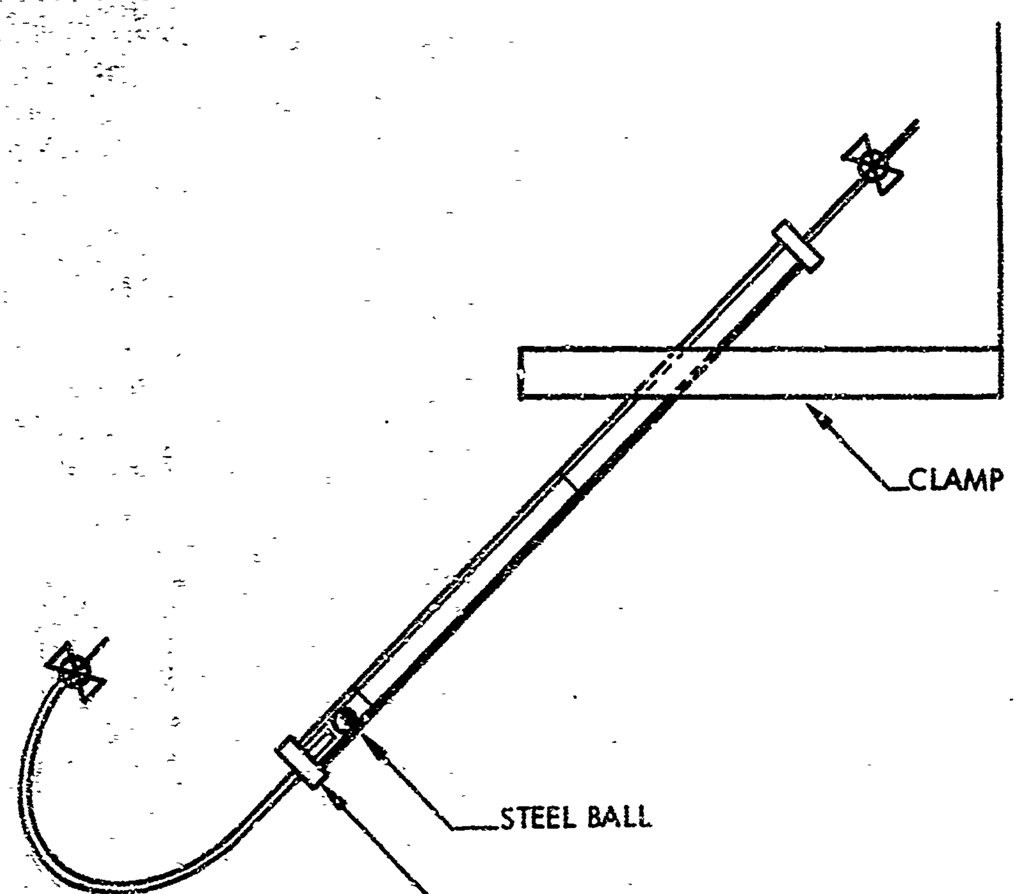


FIGURE 24

VISCOMETER LOADING SCHEMATIC

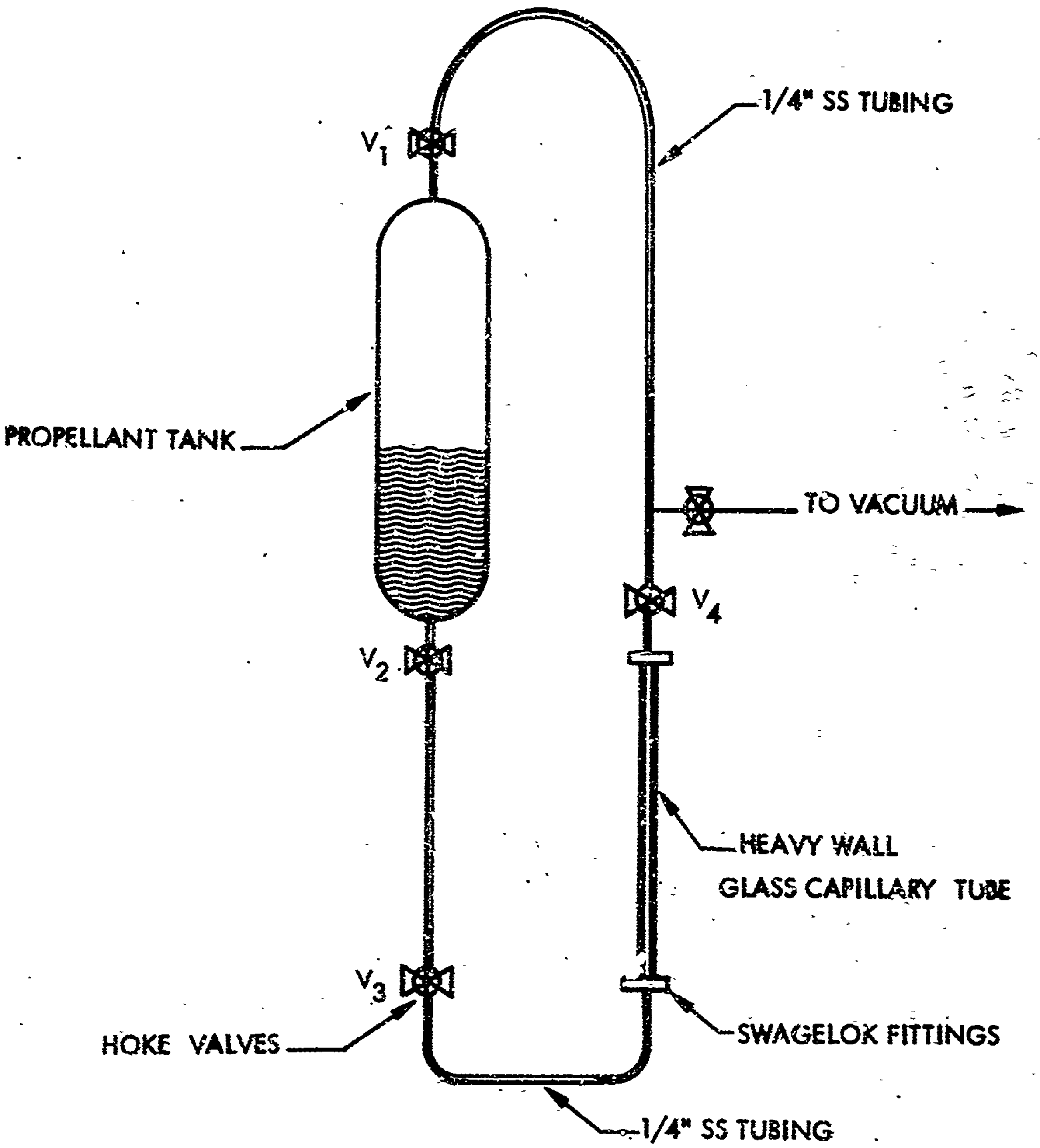


FIGURE 25

TEMPERATURE EFFECT ON VISCOSITY
OF N_2H_4 + H_2O SOLUTIONS

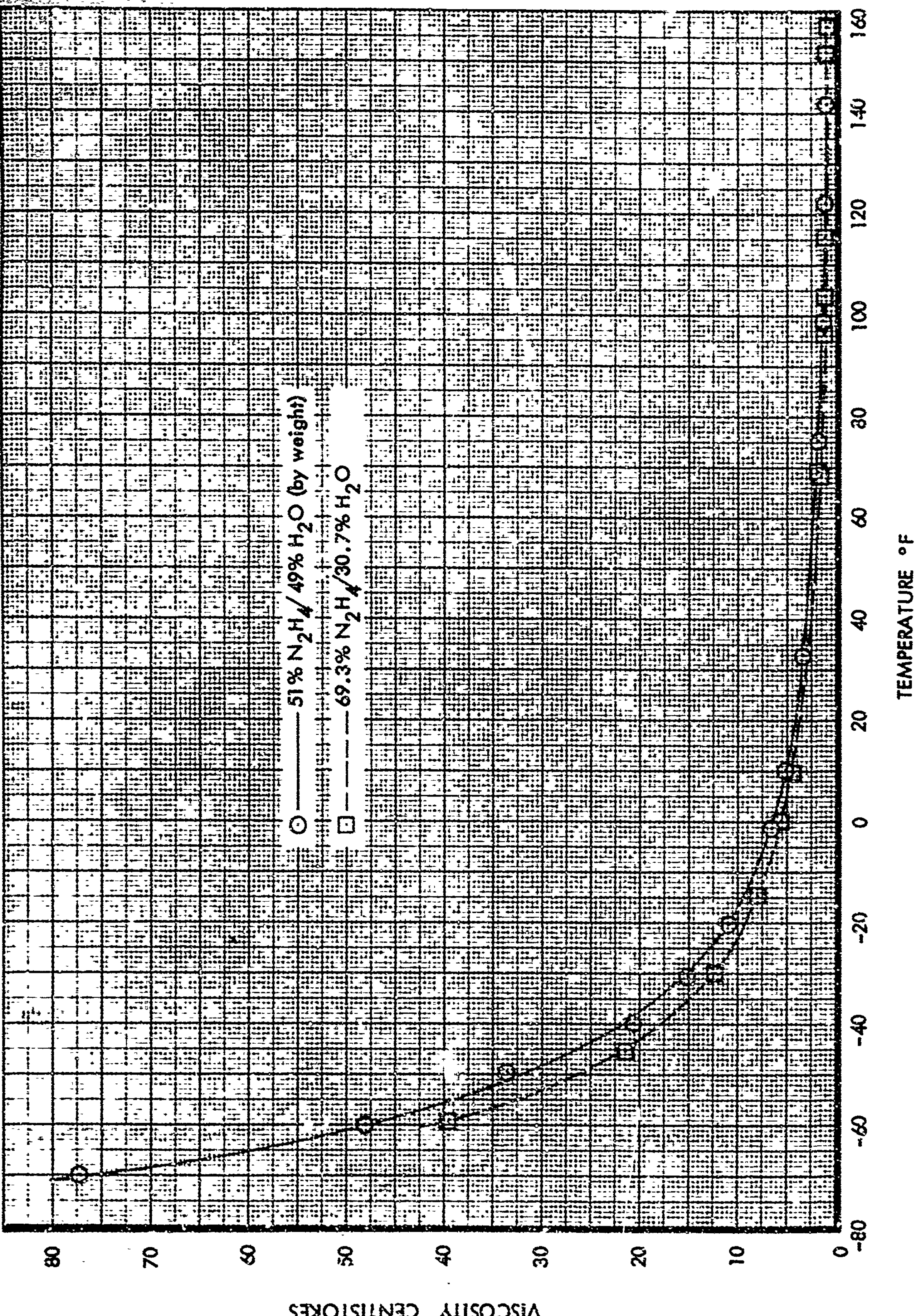
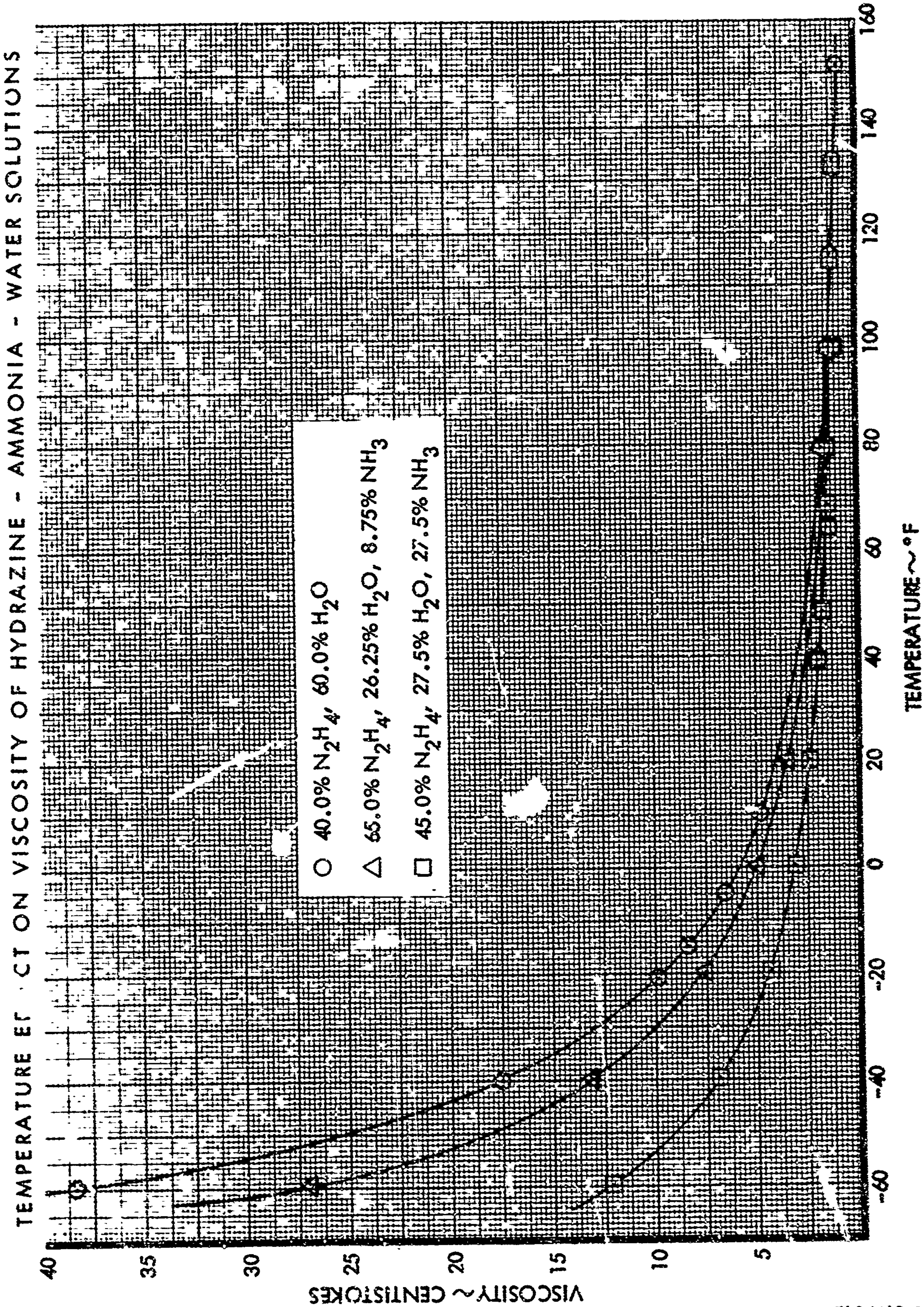


FIGURE 26

22041



TEMPERATURE EF CT ON VISCOSITY OF HYDRAZINE - AMMONIA - WATER SOLUTIONS
○ 40.0% N_2H_4, 60.0% H_2O
△ 65.0% N_2H_4, 26.25% H_2O, 8.75% NH_3
□ 45.0% N_2H_4, 27.5% H_2O, 27.5% NH_3
TEMPERATURE ~ °F
VISCOSITY ~ CENTISTOKES
-60 -40 -20 0 20 40 60 80 100 120 140 160
40 35 30 25 20 15 10 5

FIGURE 27

TEMPERATURE EFFECT ON VISCOSITY

OF HYDRAZINE - AMMONIA - WATER SOLUTIONS

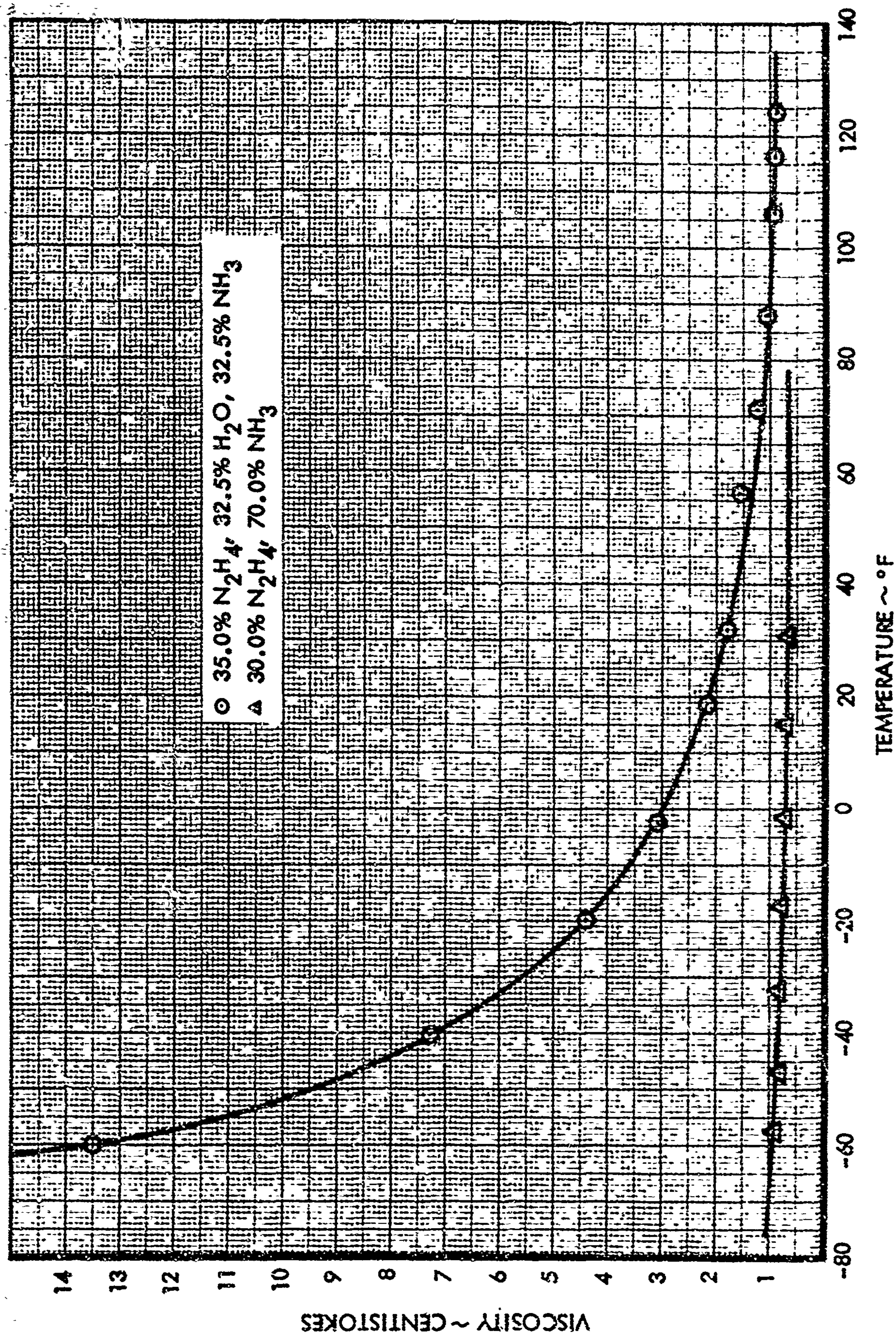


FIGURE 28

the capillary tubes were closed by pressure stopcocks. This pycnometer was loaded by the same technique used for the rolling-ball viscom. er. The pycnometer was weighed before and after loading and, after thermal eq librium was established, the liquid level in each arm of the pycnometer was determined by a cathetometer. The pycnometer was calibrated with both mercury and distilled water. This pycnometer was used for the solutions containing 8.75% and 27.5% ammonia. On the latter solution, however, the pressure stopcocks developed leaks at the higher temperatures and the use of this pycnometer was discontinued.

In order to accurately measure the density of the solutions containing 27.5%, 32.5% and 70% ammonia, individual pycnometers were blown from heavy wall glass tubing, and each pycnometer was calibrated with freshly boiled distilled water. The sample was loaded into the pycnometer as before, and after freezing the sample in liquid nitrogen, each arm of the pycnometer was sealed off with a hand torch. As a safety precaution, the pycnometer was then warmed slowly to slightly above room temperature and then cooled to room temperature before weighing. The pycnometers were then immersed in a controlled temperature bath and the liquid level in each arm was determined by means of a cathetometer. It is believed the possible error associated with this method is less than 0.1%. The measured densities are shown in Figures 29 through 33 as a function of temperature.

3.4 Summary of Propellant Physical Properties

The compositions and measured physical properties of the seven selected propellants are summarized in Table VIII.

TEMPERATURE EFFECT ON DENSITY OF N_2H_4 + H_2O SOLUTIONS

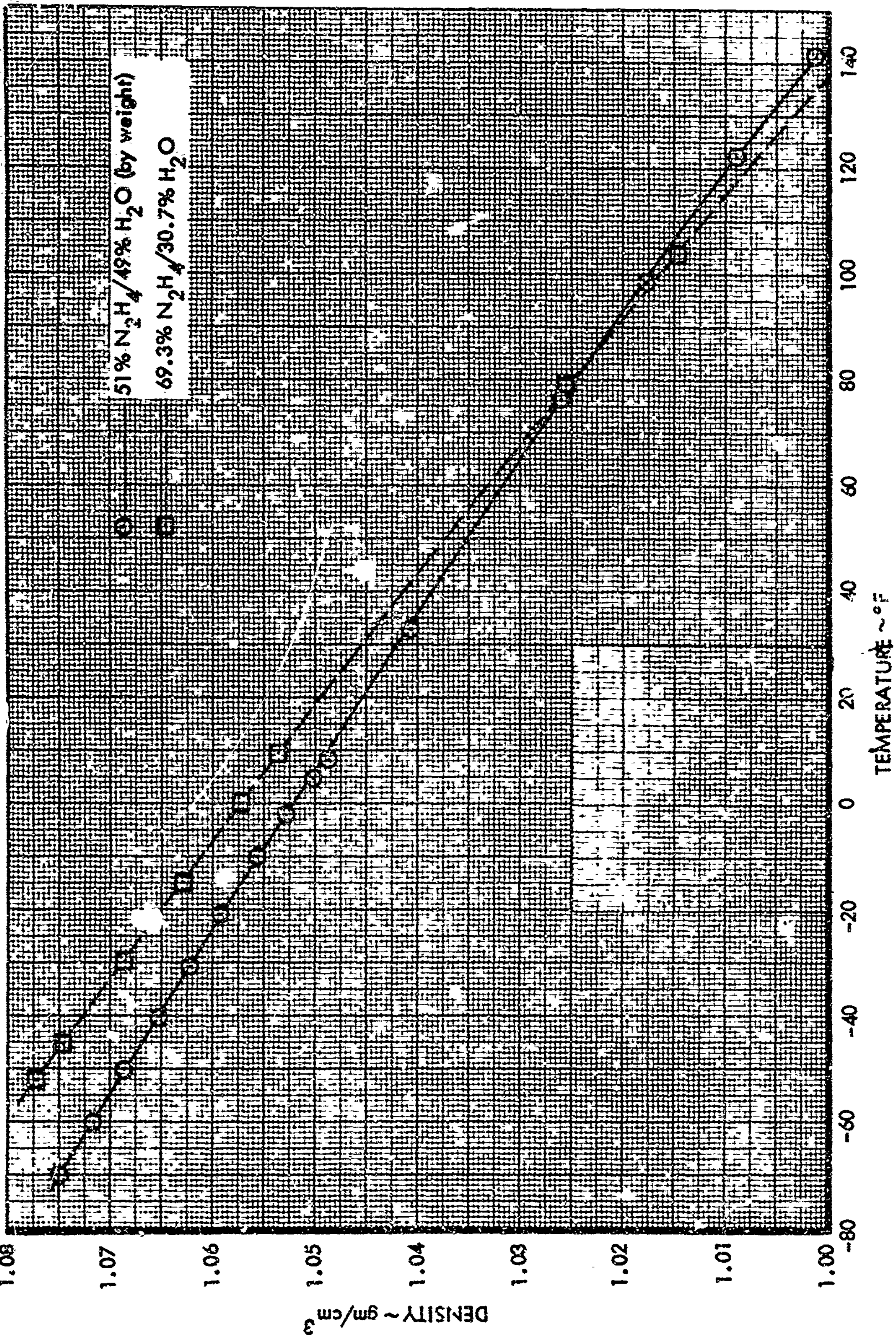
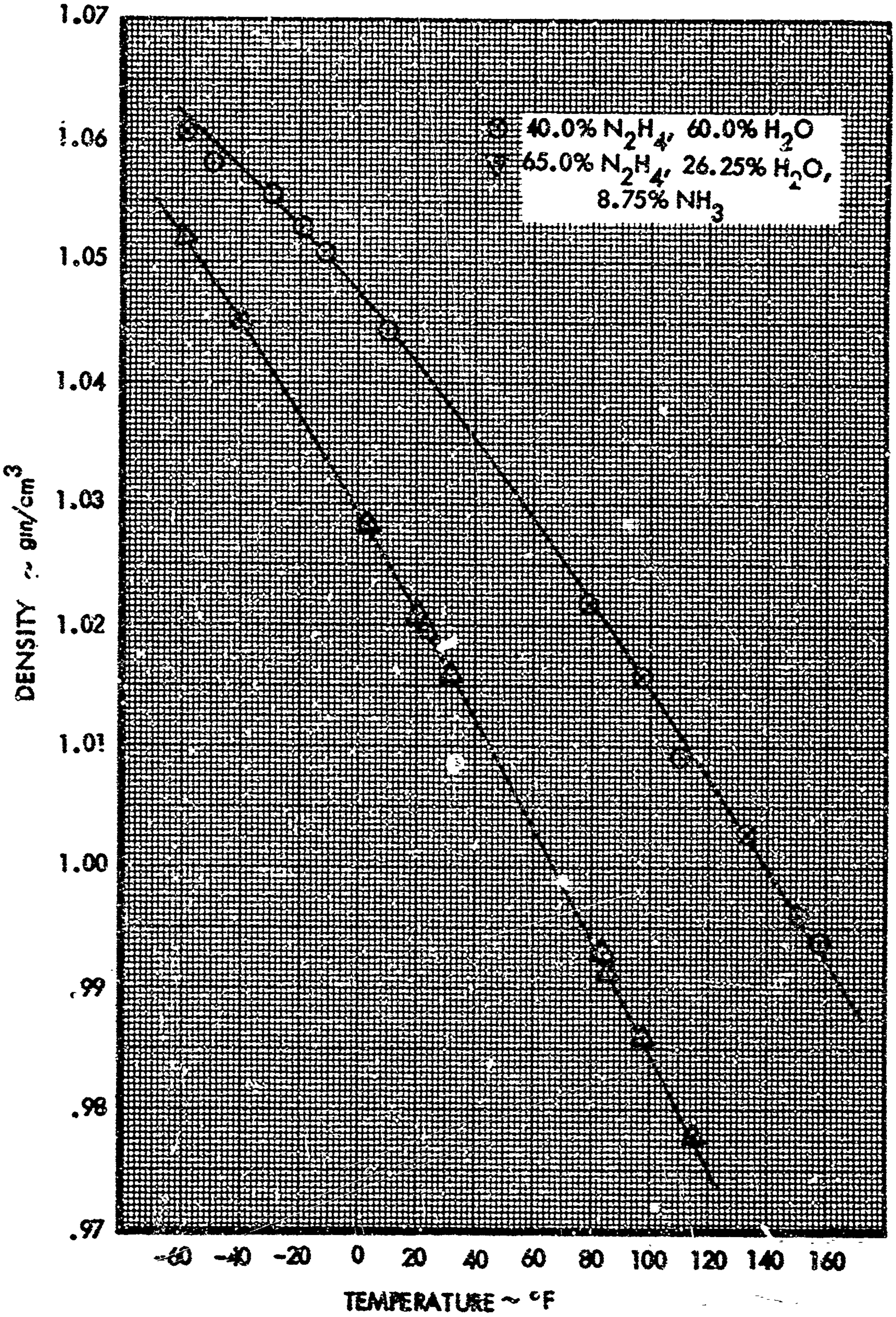


FIGURE 29

TEMPERATURE EFFECT ON DENSITY

40.0% N_2H_4, 60% H_2O AND 65.0% N_2H_4, 26.25% H_2O, 8.75% NH_3



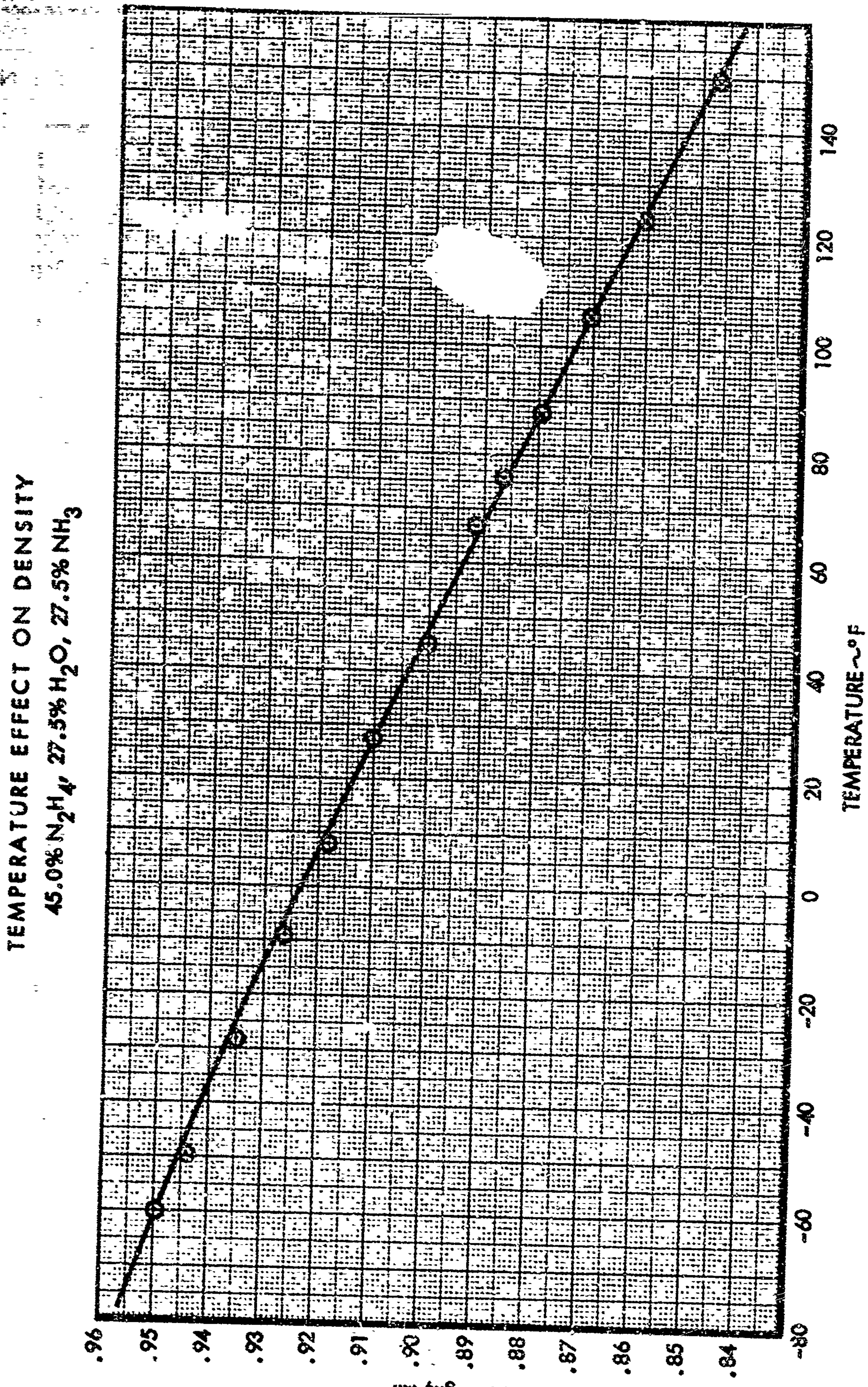
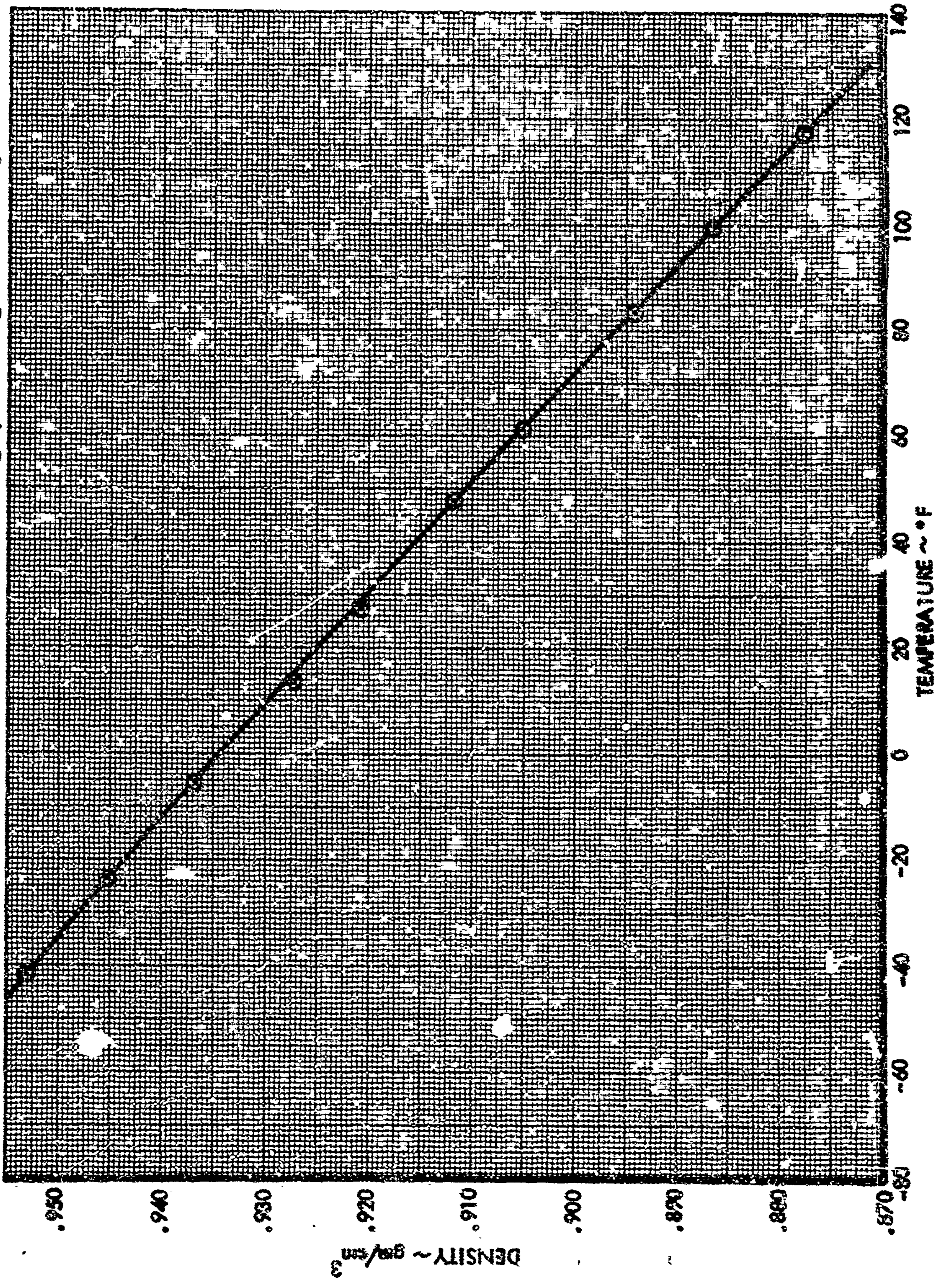


FIGURE 31

51121

TEMPERATURE EFFECT ON DENSITY 35.0% N_2H_4, 32.5% H_2O, 32.5% NH_3



TEMPERATURE EFFECT ON DENSITY

30.0% N_2H_4, 70% NH_3

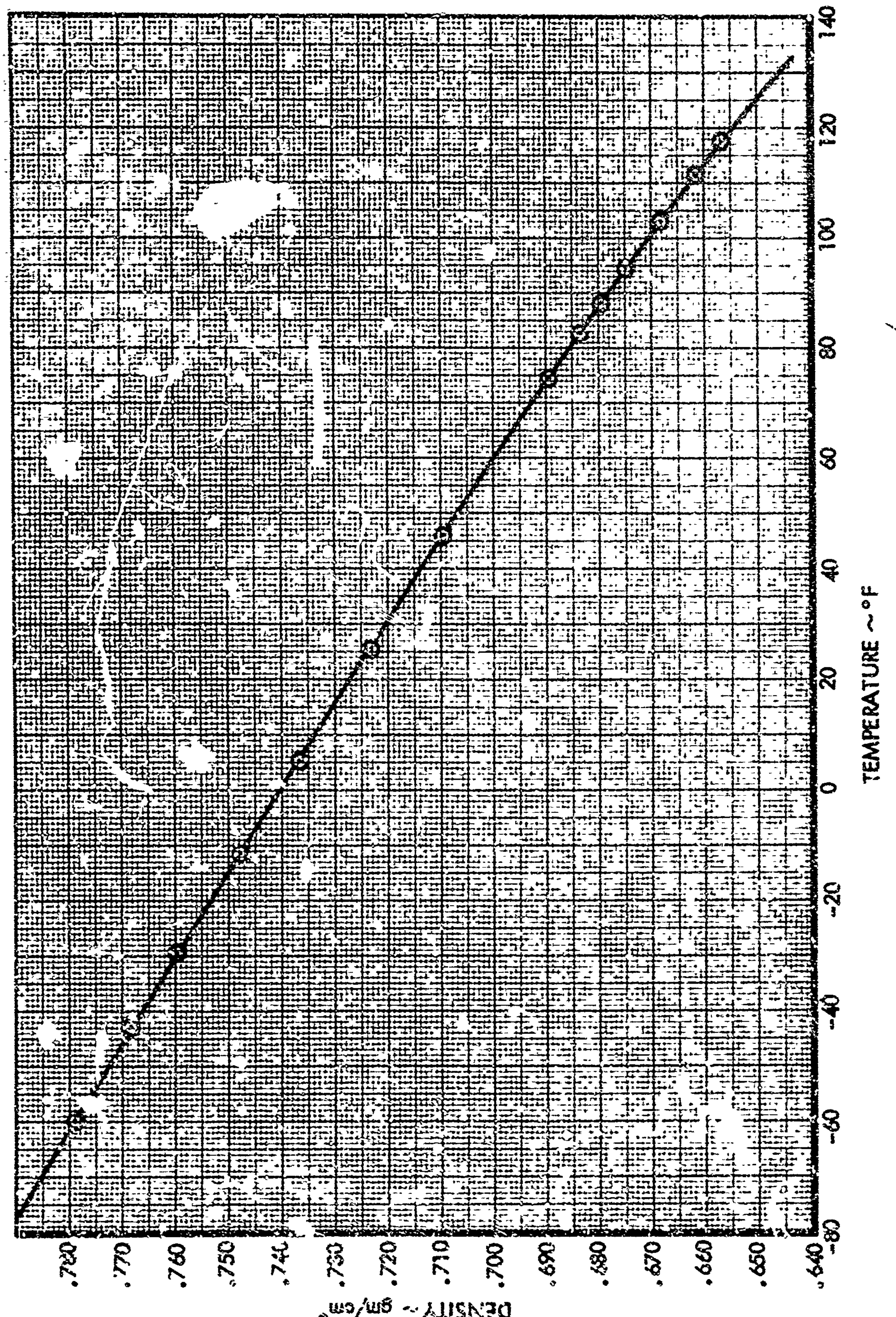


FIGURE 33

51120

TABLE VIII

PHYSICAL PROPERTIES OF LOW TEMPERATURE GAS GENERATOR PROPELLANTS

Wt. % N_2H_4	Wt. % H_2O	Wt. % NH_3	Freezing Point °F	Viscosity Centistokes at °F			Density gm/cm^3 at °F			Vapor Pressure psig at °F		
				120	+70	-60	120	+70	-60	120	+70	-60
69.3	30.7	--	-64	1.0	1.8	40.0	1.008	1.029	1.082	.83	.24	~0
45.0	27.5	27.5	-90	0.9	1.2	12.0	.863	.889	.949	87	28	~0
.0	32.5	32.5	-104	0.9	1.2	13.5	.876	0.901	0.960	103	42	~0
40.0	60.0	---	-130	0.9	1.5	38.3	1.008	1.025	1.064	1.0	.25	~0
51.0	49.0	--	-80	1.0	1.8	48.2	1.010	1.028	1.072	.83	.22	~0
30.0	--	70.0	-75	0.6	0.7	0.9	0.654	0.692	0.779	218	91	~0
65.0	26.25	8.75	-57	1.0	1.5	26.9	.975	.999	1.052	33	7	~0

(Reverse Side Blank)

SECTION IV

REACTOR TEST PHASE

4.1 General

Phase III of this program provided for the design and fabrication of a heavyweight gas generator reactor to be used to evaluate the low temperature gas generator propellants which were selected during Phases I and II. The propellant evaluation firings were to consist of two, sixty-second steady state firings for each propellant. These tasks were completed as described in detail in later sections of this report.

Due to the completion of another contract (NAS 9-5617) by Rocket Research Corporation coincident with the start of Phase III of this contract, it was possible to obtain much more performance data than provided for by the minimum requirements of the contract. In addition to the two steady state firings using the Low Temperature Gas Generator (LTGG) reactor, many firings were made using a 1 lbf thruster unit developed under the NASA contract. The 1 lbf thruster was operated for [illegible]0 pulses of varying pulse width and duty cycle on the seven selected propellant mixes, thereby providing much valuable information on the operating characteristics of the low temperature propellants.

4.2 Gas Generator Design

An assembly drawing of the gas generator is shown in Figure 34. The gas generator consists of three basic parts:

a. An orificed showerhead injector utilized to distribute the propellant onto the catalyst bed

b. A cylindrical chamber which contains the catalyst bed

c. A convergent section which has the capability of replacement of sonic orifices used to control the flow of the gas generator.

The design assumptions and calculations upon which the gas generator is based are described in the ensuing paragraphs.

The gas generator is designed to decompose selected mixtures of hydrazine, water, and/or ammonia as tabulated in Table VIII. The basic design parameters for the engine are: a chamber pressure of 300 psia, a volumetric flow rate of 60 scfm, and an ammonia dissociation with neat hydrazine of 80%. The design of the gas generator is based on

LOW TEMPERATURE GAS GENERATOR ASSEMBLY

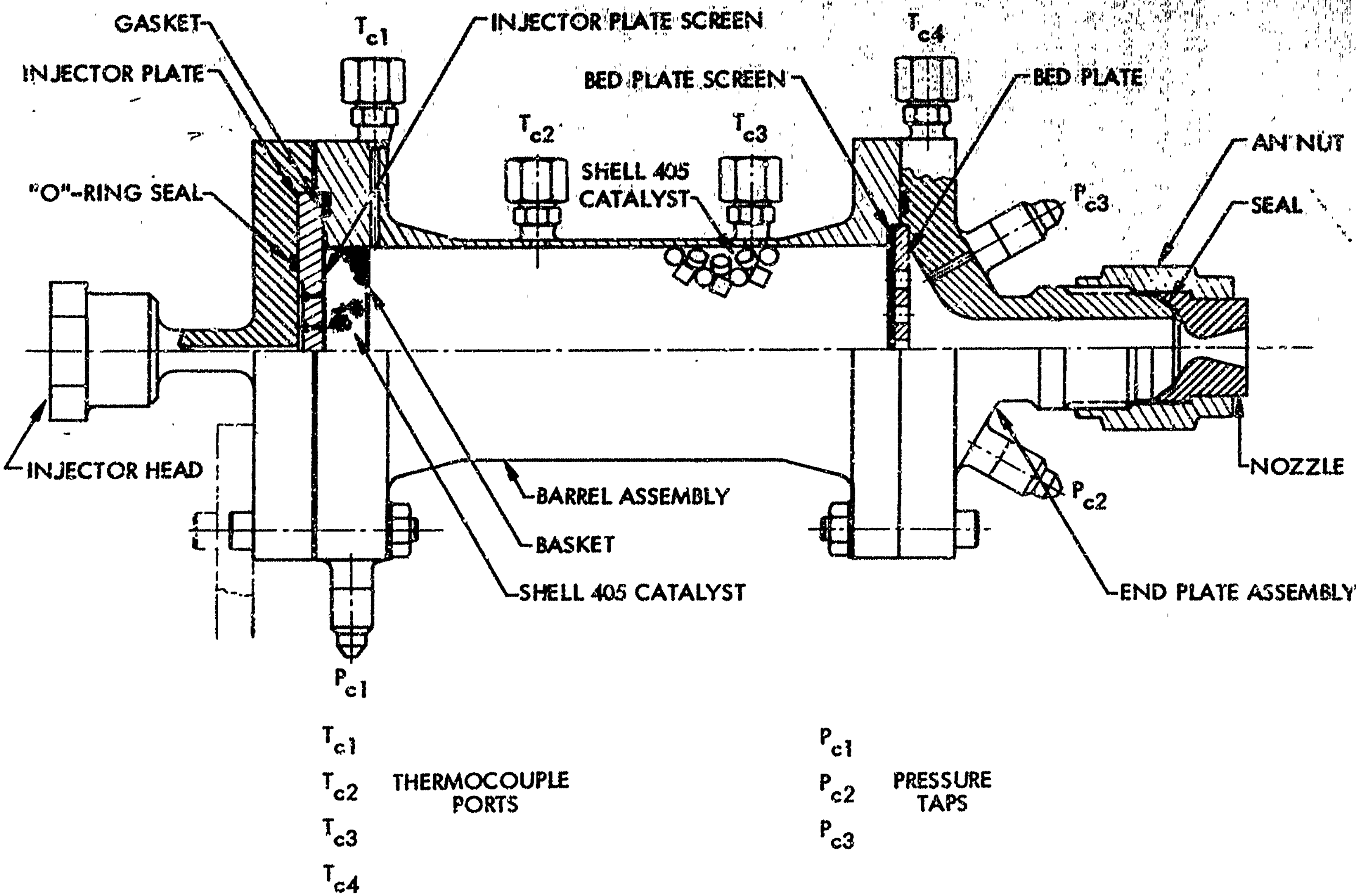


FIGURE 34

design criteria developed by Rocket Research Corporation under NASA Contracts NAS 7-372 and NAS 9-5617.

Under NASA Contract NAS 7-372, it was shown that a layer of fine mesh catalyst (25 - 30 mesh) approximately 0.2 to 0.3 inches in thickness is required at the top of the catalyst bed to insure smooth and stable operation. The remainder of the catalyst bed is composed of larger size catalyst such that the ratio of chamber diameter to particle size diameter is at least 8:1. A bed loading of 0.0274 was selected for the gas generator. From the definition of bed loading, the chamber diameter is calculated to be 1.50 inches. The catalyst size in the lower portion of the bed is 1/8" x 1/8" pellets (largest size manufactured by Shell Development Company).

The average molecular weight of the gas products from the hydrazine mixtures is 18.72 if it is assumed no ammonia dissociation occurs as a result of the high water content in the mixtures. Using the perfect gas law, the reactor flow rate is then calculated as:

$$\dot{w} = \frac{P_s \bar{M}}{R T_s} \dot{V}$$

Where:

$\dot{w}$ = Propellant flow rate, lbm/sec

R = Universal gas constant

P_s = Standard Atmospheric Pressure, lbf/ft^2

T_s = Standard Temperature, °R

$\bar{M}$ = Average Gas Product molecular weight, lb/lb mole

$\dot{V}$ = Volumetric flow rate, scfs

Thus:

$$\dot{w} = \frac{(2116)(18.7)(1)}{(1544)(530)} = 0.0483 \text{ lbm/sec}$$

Under NASA Contract NAS 7-372, the following equation was developed to predict ammonia dissociation in the catalyst bed with neat hydrazine and using 1/8" x 1/8" cylindrical catalyst pellets:

$$\ln(1 - X) = - \quad 0.472 + 910 \frac{G^{0.71} t}{P}$$

Where:

X = Fractional ammonia dissociation

G = Bed loading, lbm/in^2-sec

t = Residence time of propellant in catalyst bed, ms

P = Chamber pressure, psia

The residence time is given by:

$$t = \frac{\epsilon L \bar{M} P}{G R T} (1000)$$

where previously undefined parameters are:

ϵ = Fractional catalyst bed porosity

L = Catalyst bed length, in.

Thus, for the design conditions of the gas generator, the catalyst bed length is calculated as:

$$\ln(1 - 0.8) = - \left[0.472 + 910 \frac{(0.0274)^{0.71}(0.340)(13.8)(1000)L}{(0.0274)(1544)(12)(2260)} \right]$$

$$1.6094 = 0.472 + 0.289L$$

$$L = 3.94 \text{ inches}$$

A catalyst bed of 4.0 inches was used for the design. It should be noted that the gas generator was designed for 80% ammonia dissociation with neat hydrazine and that when operated with the propellant mixtures, the ammonia dissociation will be less because of the flame temperature reduction from diluent addition.

The injector design is based on criteria developed under NASA Contract NAS 7-372. This criteria for a showerhead injector is:

a. Use a pressure drop across the injector of 15% of steady state chamber pressure

b. Use an orifice density of 6 orifices per square inch of catalyst bed cross-sectional area.

Thus the injector utilizes 12 orifices with a pressure drop of 45 psid. Table IX summarizes the gas generator design parameters.

4.3 Reactor Testing

Schematic drawings of the LTGG and the 1 lbf thruster are shown in Figures 35 and 36. The test set-up is illustrated schematically in Figure 37. The various instrumentation parameters are listed in Table X. A typical run sequence involved the following steps.

a. Propellant was loaded into the precleaned and nitrogen dried run tank through a 10 micron filter.

b. Flowmeters were calibrated.

c. Two 60-second steady state firings were carried out with the LTGG at a nominal chamber pressure of 300 psia. An exhaust gas sample was taken during each firing in a pre-evacuated sample bottle. The gas sample flow was initiated approximately 40 seconds after ignition and sampling was continued until a sample pressure of approximately 50 psig was obtained.

d. After the second LTGG firing on each fuel mix, the gas generator was removed from the system and oven purged at 250°F for 15 minutes with dry, filtered (10 micron) gaseous nitrogen.

e. A single 30-second steady state firing of the 1 lbf thruster was conducted at a nominal chamber pressure of 70 psia followed as soon as possible by the pulse mode firing sequence listed in Table XI.

f. Upon completion of the firing sequence, the 1 lbf thruster was removed from the system and oven purged as described in Step d.

4.3.1 Propellant Preparation

The propellant was prepared by weighing the required amount of water in a polyethylene carboy and adding anhydrous hydrazine by pressurizing the storage

TABLE IX

GAS GENERATOR DESIGN PARAMETERS

Chamber Pressure	300 psia
Volumetric Flow Rate	60 scfm
Propellant Flow Rate	0.0483 lbm/sec
Predicted Ammonia Dissociation (Neat Hydrazine)	80%
Catalyst Bed Diameter	1.5 inches
Catalyst Bed Length	4.0 inches
Catalyst Size	0.3 inches 25-30 Mesh 3.7 inches 1/8" x 1/8" pellets
Injector Type	Showerhead
Number of Orifices	12
Injector Pressure Drop	45 psid
Catalyst Bed Pressure Drop	~ 4 psid

LTGG REACTOR INSTRUMENTATION

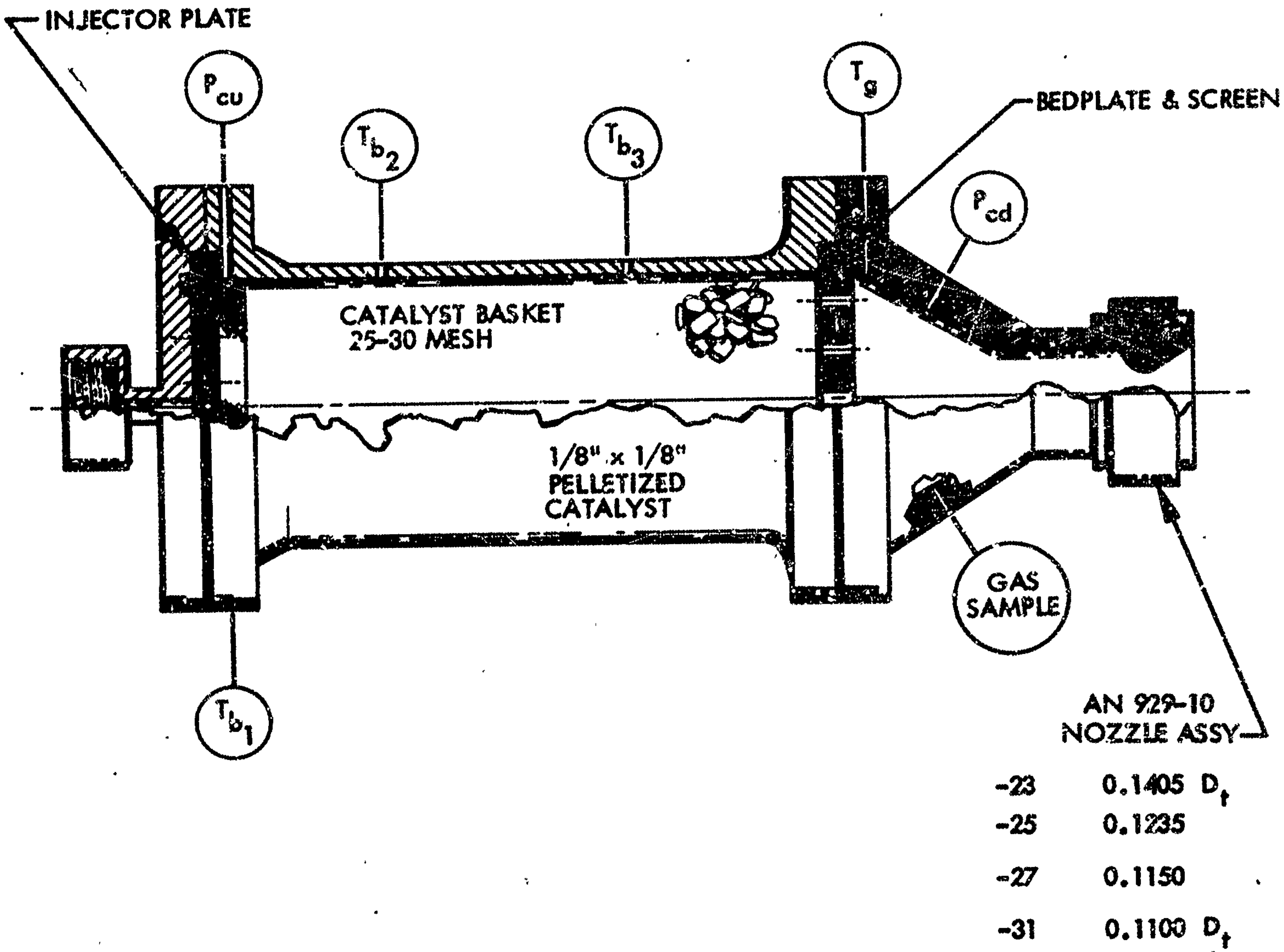


FIGURE 35

1 lbf THRUSTER INSTRUMENTATION

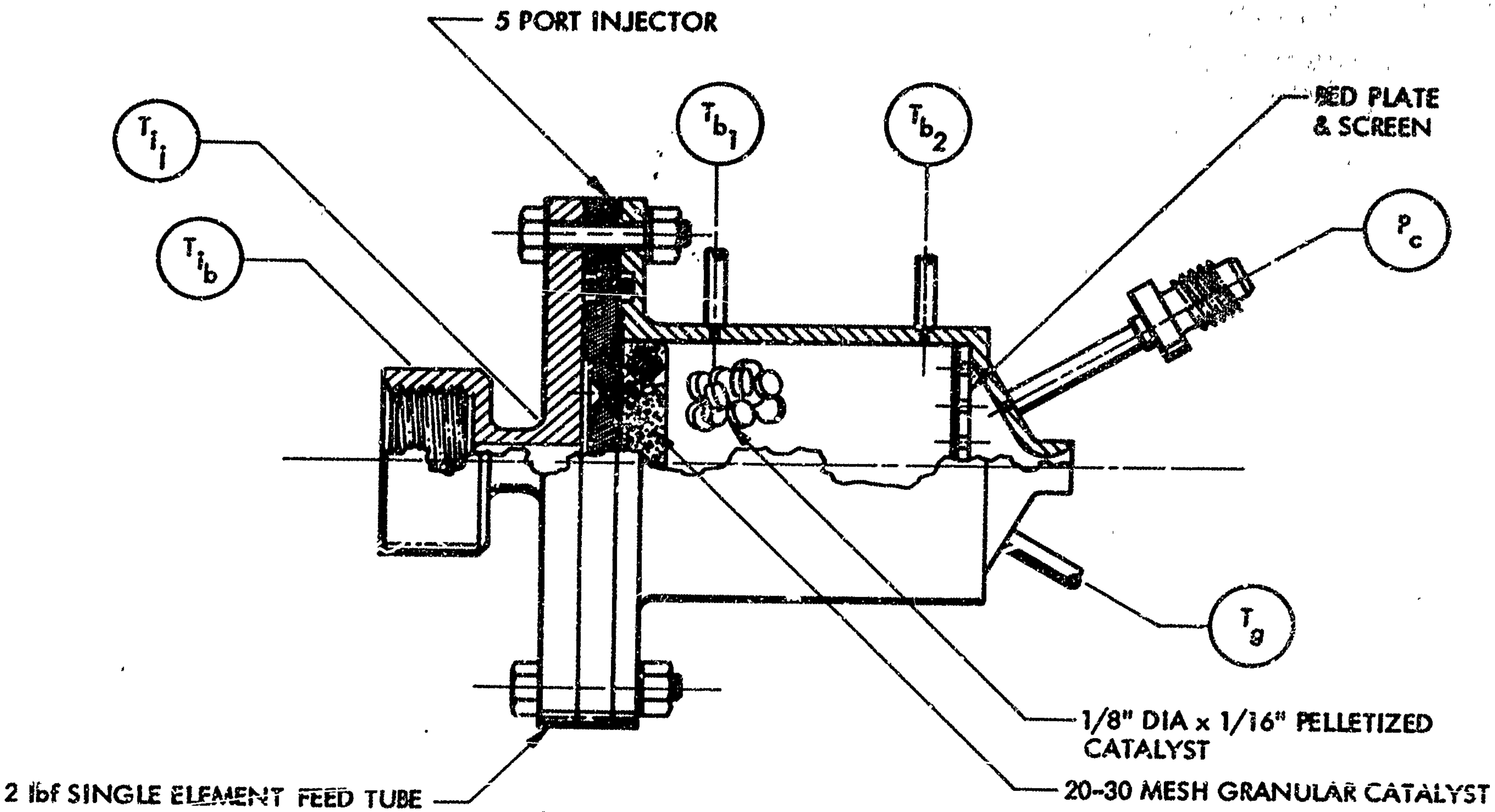


FIGURE 36

REACTOR TEST SCHEMATIC

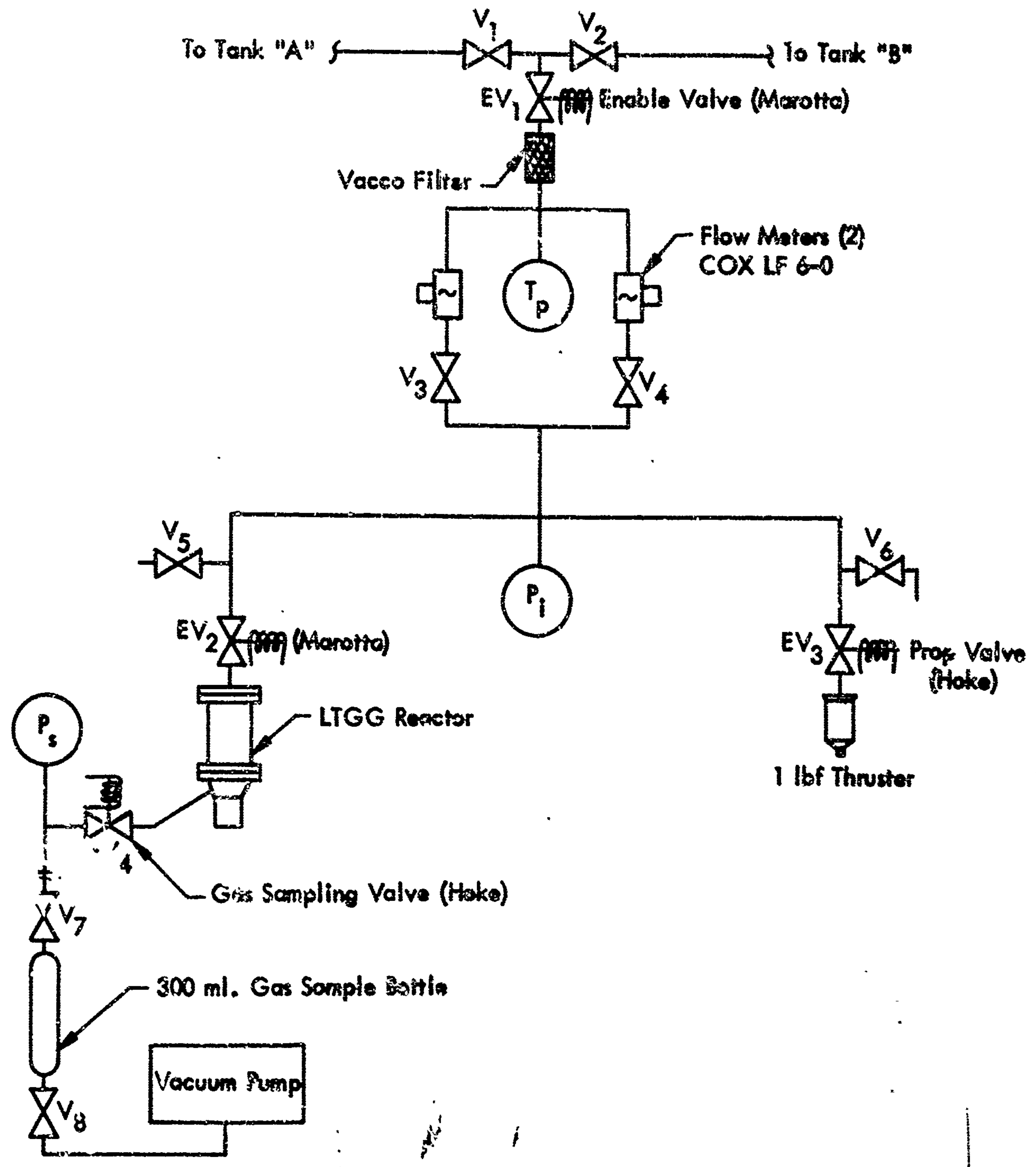


FIGURE 37

TABLE X

INSTRUMENTATION PARAMETERS

Parameter Symbol	Parameter Identification
P_i System	Injector Pressure
T_p System	Propellant Temperature
P_s (LTGG)	Gas Sample Pressure
P_{cd} (LTGG)	Chamber Pressure (Downstream)
P_{cu} (LTGG)	Chamber Pressure (Upstream)
T_{b1} (LTGG)	Bed Temperature (Top)
T_{b2} (LTGG)	Bed Temperature (Mid)
T_{b3} (LTGG)	Bed Temperature (Bottom)
T_g (LTGG)	Gas Temperature
$\dot{w}_{p1}$ (LTGG)	Propellant Flow Rate
$\dot{w}_{p2}$ (LTGG)	Propellant Flow Rate
V_{p1} (LTGG)	Propellant Valve Position
P_c (1 lbf)	Chamber Pressure
T_g (1 lbf)	Gas Temperature
T_{ib} (1 lbf)	Injector Boss Temperature
T_{ig} (1 lbf)	Injector Temperature
T_{b1} (1 lbf)	Bed Temperature (Top)
T_{b2} (1 lbf)	Bed Temperature (Bottom)
$\dot{w}_{p1}$ (1 lbf)	Propellant Flow Rate
V_{p2} (1 lbf)	Propellant Valve Position

TABLE XI

PULSE MODE FIRING SEQUENCE

No. of Pulses	On Time (seconds)	Off Time (seconds)	Duty Cycle %
50	0.25	0.25	50
50	0.25	0.25	10
50	1.0	1.0	50
50	1.0	9.0	10
25	3.0	3.0	50
25	3.0	27.0	10
20	7.0	7.0	50
20	7.0	63.0	10

container with nitrogen and forcing the hydrazine through a transfer tube into the mixing container until the proper total weight was obtained. The hydrazine was analyzed for water content and the results of the analysis were used in calculating the required weight of hydrazine and water.

The propellants containing ammonia were prepared in the same way to obtain the required hydrazine-water solution. The ammonia (liquid) was then added through a "flexible" line until the required total weight was obtained plus a slight excess. The line was then removed and the excess ammonia was bled off slowly until the required total weight was obtained. Any possible error in weighing due to the influence of the line was therefore eliminated.

4.3.2 Flowmeter Calibration

Calibration of the turbine flowmeters was attempted by flowing the propellant from one pressurized tank to another with both tanks pressurized to above the vapor pressure of the propellant. A constant flow rate could not be maintained by this method, however, and the accuracy of the resultant data was questionable. The propellant flow rate was therefore estimated by utilizing a universal calibration curve* which can be readily developed by water calibration. The accuracy of this approach is estimated to be within ±2% and in all probability is better than this value due to the small changes in viscosity of the NH_3 mixes as compared to the viscosity of water.

4.4 Results of Test Firings

The results of the LTGG evaluation tests are shown in Table XII, while the results of the 1 lbf thruster test firings are summarized in Table XIII. The theoretical range listed is based on temperatures possible for different percentages of ammonia dissociation. For the LTGG reactor, agreement among the three catalyst bed temperatures and exhaust temperature was reasonably good with the exception of the mixture containing 60% water. In this case, the exhaust gas temperature was from 60 to 100 degrees lower than the three bed temperatures and the theoretical temperature.

The chamber pressure of the LTGG reactor was within 7 psia of the nominal 300 psia except for the two mixtures containing less than 40% hydrazine. These mixtures operated

* Plot of cycles per gallon vs. cycles per second/viscosity.

TABLE XIII

LGG REACTOR TEST DATA

Composition % by Weight	Maximum Chamber Pressure P_{cd} – psia [1]	Chamber Pressure Roughness % of P_{cd}	Catalyst Bed Pressure Drop $P_{cu} - P_{cd}$	Exhaust Gas Temperature T_g – °F	Propellant Supply Temperature T_p – °F	Upper Catalyst Bed Temp. T_{b1} – °F	Mid Catalyst Bed Temperature T_{b2} – °F	Lower Catalyst Bed Temp. T_{b3} – °F	Ignition Delay milliseconds [2]	Response Time milliseconds [3]	Upper Catalyst Bed Temperature Prior to Ignition T_{b1} – °F	Characteristic Exhaust Velocity c^* – ft/sec [1]	L^* (Empty Chamber)	Comments
N_2H_4–65.0% H_2O–26.25% NH_3–8.75%	293 295	± 1% ± 1%	6 psi 8 psi	1062 1082 882 to 1262 Theo	58 58	1122 1026	1066 1059	1063 1065	40 40	160 130	172 260	3029 3025 3000 – 3250 Theo	500 in.	Replaced catalyst screen after run due to generation of fines. Smooth running run. No chamber pressure over-shoot on start-up.
N_2H_4–45.0% H_2O–27.5% NH_3–27.5%	297 297	± 1% ± 1%	38 psi 38 psi	422 422 2573 to 4773 Theo	42 42	405 405	405 405	405 438	35 30	250 270	26 195	2390 2396 2620–2725 Theo	650 in.	Extremely smooth running run. No chamber pressure over-shoot on start-up.
N_2H_4–30.0% NH_3–70.0%				730 730 Set to 2718 Theo	66 66	458 458	1103 1102	1020 1020	30 30	540 1700	95 55	1523–2573 Theo	750 in.	Extremely poor reactor performance. Chamber pressure decayed during run while fuel rate increased. Reactor cold to touch on top of bed, & just barely warm on exhaust nozzle end.
N_2H_4–25.0% H_2O–37.5% NH_3–37.5%	200 [illegible]		5 psi [illegible]	2396 Theo	62 62							2264 Theo	800 in.	Poor reactor performance. Chamber pressure decayed during run. Was short-lived start & long ignition delay.
N_2H_4–57% H_2O–43%	305 305	± 2% ± 1%	4 psi 4 psi	541 544 4259 Theo	75 75	532 524	540 543	542 543	45 30	380 229	77 979	2546 2597 2384 Theo	450 in.	No chamber pressure over-shoot on start-up. Smooth.
N_2H_4–60% H_2O–40%	299 295	± 1% ± 1%	4 psi 4 psi	2981 283 3125–2647 Theo	1028 1102	362 362	362 362	362 362	320 30	1230 960	77 160	2427 2323 1932–2068 Theo	800 in.	Exhaust very wet. Operation stable and capable of sustained operation; smooth operation no overshoot on start.
N_2H_4–69.7% H_2O–30.3%	300 306	± 1% ± 1%	8 psi 8 psi	1127 1129 901–1362 Theo	114 109	1198 1208	1192 1192	1160 1167	30 30	210 290	34 309	3582 1574 3050–2264 Theo	540 in.	Very smooth running run. No chamber pressure over-shoot on start-up.

1. Measured during final five seconds of nominal 60 second run. 2. Valve full open to 1% chamber pressure rise. 3. Valve full open signal to 90% chamber pressure rise.

TABLE XIII

ENGINE THRUSTER TEST DATA SUMMARY

Propellant Composition (% by Weight)	Thruster On-Time Seconds	Duty Cycle [1]	Chamber Pressure P_c - psia [2]	Chamber Pressure Roughness % of P_{c}	Exhaust Gas Temperature T_g - °F [3]	Propellant Supply Temperature T_p	Upper Catalyst Bed Temp. T_{BUA} - °F [3]	Lower Catalyst Bed Temp. T_{BLA} - °F [3]	Ignition Delay Milliseconds [4]	Response Time Milliseconds [5]	Characteristic Exhaust Velocity c^* - ft/sec.	Comments
N_2H_4-37% H_2O-63%	.25	50	73	± 5%	NA	82°F	570	580	—	—	2388	N_2 overshoot - stable operation, good running mix.
	.25	10	67	± 5%	NA	80	598	554	10	152	2316	
	1.00	50	75	± 5%	NA	83	585	578	5	210	2526	
	1.00	10	69	± 5%	NA	80	528	567	5	248	2420	
	3.00	50	70	± 5%	NA	77	590	598	15	170	2442	
	3.00	10	70	± 5%	NA	75	590	570	NA	NA	—	
	7.00	50	69	± 5%	NA	75	570	602	5	140	2525	
	7.00	10	69	± 5%	NA	75	525	585	5	140	2424	
					425 Theo						2384 Theo	
N_2H_4-40% H_2O-60%	.25	50	66	± 5%	247	73	259	259	—	—	NA	No overshoot - stable operation, very wet exhaust.
	.25	10	59	± 5%	247	77	132	234	30	NA	1346	
	1.00	50	65	± 5%	253	68	256	236	NA	NA	1690	
	1.00	10	64	± 5%	254	73	256	256	20	650	1576	
	3.00	50	67	± 5%	256	62	260	260	NA	NA	1729	
	3.00	10	68	± 5%	256	68	260	260	NA	NA	1722	
	7.00	50	67	± 5%	255	59	260	260	NA	NA	—	
	7.00	10	67	± 5%	256	66	260	260	50	820	1717	
					325-368 Theo						1952-2000 Theo	
N_2H_4-69.3%	.25	50	72	± 5%	NA	73	1045	1052	—	—	1222	No chamber pressure overshoot on start. Stable operation.
H_2O-30.7%	.25	10	71	± 5%	NA	77	1078	1072	5	60	3033	
	1.00	50	71	± 5%	NA	73	1080	1070	5	50	3267	
	1.00	10	71	± 5%	NA	80	1105	1070	10	60	3293	
	3.0	50	71	± 5%	NA	70	1116	1082	5	50	3255	
	3.0	10	71	± 5%	NA	73	1115	1077	10	60	3299	
	7.00	50		± 5%	NA	66	1116	1097	10	60	3351	
	7.00	10	71	± 5%	NA	77	1116	1116	5	80	3252	
					923-1302 Theo						3136-3384 Theo	

1. % On Time 2. Maximum Value Measured 3. Maximum Value Measured 4. Valve Open Signal to 5% Chamber Pressure Rise 5. Valve Open Signal to 90% Chamber Pressure Rise

TABLE XIII (Cont'd)

1 lbf THRUSTER TEST DATA SUMMARY

Propellant Composition (% by Weight)	Thruster On-Time Seconds	Duty Cycle [1]	Chamber Pressure P_c – psia [2]	Chamber Pressure Roughness % of P_{cd}	Exhaust Gas Temperature T_e – °F [3]	Propellant Supply Temperature T_p	Upper Catalyst Bed Temp. T_{BTA} – °F [3]	Lower Catalyst Bed Temp. T_{BBA} – °F [3]	Ignition Delay Milliseconds [4]	Response Time Milliseconds [5]	Characteristic Exhaust Velocity c^* – ft/sec	Comments
N_2H_4 –	.25	50	69	± 8%	929	82	1010	980	—	—	3252	Replaced catalyst section after run due to fines generation.
65.0%	.25	70	68	± 8%	923	90	955	942	40	100	2713	
H_2O –	1.00	50	70	± 4%	989	86	1032	998	25	150	2875	Approximately 8% overshoot on chamber pressure on start-up.
26.25%	1.00	70	70	± 4%	926	82	1032	948	60	240	2925	
NH_3 –	3.00	50	69	± 5%	1024	75	1095	1032	20	230	2994	Smooth running mix.
8.75%	3.00	70	68	± 6%	976	80	1095	1032	90	280	2723	
	7.00	50	69	± 6%	1040	75	1095	1070	40	160	3037	
	7.00	70	68	± 6%	1032	80	1095	1073	100	250	2583	
					920-1240 Trans							
N_2H_4–45.0%	.25	50	69	± 8%	390	78	386	357	—	—	1928	Smooth running mix. No chamber pressure overshoot on start-up.
H_2O–27.5%	.25	70	63	± 8%	390	82	390	357	30	90	1557	
NH_3–27.5%	1.00	50	68	± 8%	400	88	400	357	—	—	2272	
	1.00	70	66	± 8%	395	79	395	406	27	430	2022	
	3.00	50	69	± 8%	420	88	396	406	30	260	2137	
	3.00	70	70	± 8%	404	77	386	409	30	405	2080	
	7.00	50	69	± 8%	390	68	386	410	30	220	2056	
	7.00	70	69	± 8%	408	75	377	398	45	430	2277	
					393-433 Trans							
N_2H_4–30.0%	.25	50										Would not sustain pulse mode operation
NH_3–70.0%	.25	70										
	1.00	50										
	1.00	70		NO DATA REDUCED	–	NO DATA REDUCED	–	NO DATA REDUCED				
	3.00	50										
	3.00	80										
	7.00	50										
	7.0_	70										

1. % On Time 2. Maximum Value Measured 3. Maximum Value Measured 4. Valve Open Signal to 1% Chamber Pressure Rise 5. Valve Open Signal to 90% Chamber Pressure Rise

TABLE VIII (Cont'd)

5 lbf THRUSTER TEST DATA SUMMARY

Propellant Composition (% by Weight)	Thruster On-Time Seconds	Duty Cycle [1]	Chamber Pressure P_c - psia [2]	Chamber Pressure Roughness % of P_{cd}	Exhaust Gas Temperature T_g - °F [3]	Propellant Supply Temperature T_p	Upper Catalyst Bed Temp. T_{UCB} - °F [3]	Lower Catalyst Bed Temp. T_{LCB} - °F [3]	Ignition Delay Milliseconds [4]	Response Time Milliseconds [5]	Characteristic Exhaust Velocity c^* - ft/sec	Comments
N_2H_4-35.2%	.25	50		NO DATA REDUCED		-	NO DATA REDUCED		-	NO DATA REDUCED		Would not sustain pulse mode operation. Could be sustained for several pulses by adjusting (manually) to constant temp.
H_2O-22.3%	.25	10										
NH_3-22.5%	1.00	50										
	1.00	10										
	3.00	50										
	3.00	10										
	7.00	50										
	7.00	10										

1. % Time 2. Maximum Value Measured 3. Maximum Value Measured 4. Valve Open Signal to 5% Chamber Pressure Rise 5. Valve Open Signal to 90% Chamber Pressure Rise

poorly and had low and decaying chamber pressures. The five mixtures which sustained reactor operation were very smooth running with chamber pressure roughness factors of within ± 1% on both reactors except for the mixture containing 65% N_2H_4. The operation of this mixture was somewhat rougher in the pulse mode tests.

The calculated c* values were in the range of 100 to 106.5% of theoretical for the LTOG reactor. The fact that the temperatures recorded were near the theoretical upper limit, and the small nozzle orifices used do not make the high c* values too surprising.

The calculated c* values are shown in Figure 38 as a function of weight percent hydrazine. The theoretical curves for hydrazine-ammonia solutions and hydrazine-water solutions are also illustrated for comparison purposes. It is believed that the dip in the theoretical curve for hydrazine-water solutions is a result of the theoretical condensation of water in the chamber with a resultant decrease in the amount of working gas.

The c* values obtained during pulse mode operation of the 1 lbf thruster are shown in Figure 39 as a function of pulse width and duty cycle. It may be observed that for pulse widths as short as 1 second, the performance approximately equals the steady state values but falls off rapidly for shorter pulses.

The 40% hydrazine-60% water mixture operated smoothly in both steady state and pulse mode operation although very long response times were observed. The propellants containing 30% and 35% hydrazine would not sustain pulse mode operation although the 35% hydrazine mixture could be forced to operate for several pulses by reheating the reactor externally to ambient temperature.

Exhaust gas samples were collected near the end of each 60-second firing of the propellant mixtures. The samples were collected in Hoke stainless steel cylinders of 300 ml capacity which were connected to the reactor (near the nozzle) through a solenoid valve and stainless steel tubing. A pressure transducer was also in the system between the valve and the cylinder to monitor the pressure in the sample cylinder. Collection of the gas sample was initiated approximately 40 seconds after ignition and continued until a sample pressure of approximately 50 psig was obtained. The chemical analysis, performed by an independent laboratory, involved heating the sample cylinder to ensure complete vaporization of the sample which was then injected into a gas chromatograph through a heated valve. The results of the initial analyses were not satisfactory, and considerable effort was expended in checking both the analysis and the sampling procedures.

PERFORMANCE AS A FUNCTION OF HYDRAZINE CONTENT

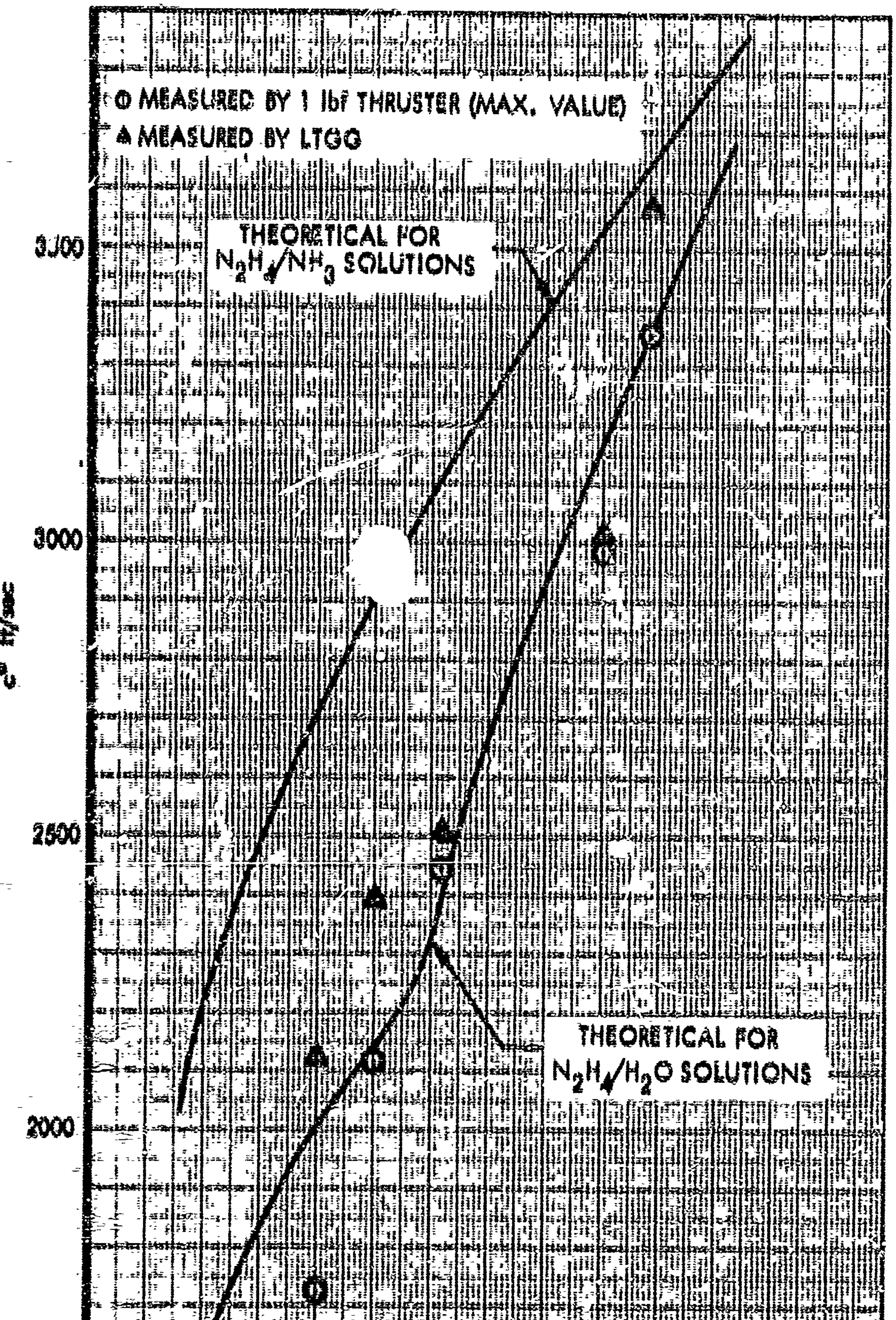


FIGURE 38

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CHARACTERISTIC EXHAUST VELOCITY
DURING PULSE MODE OPERATION

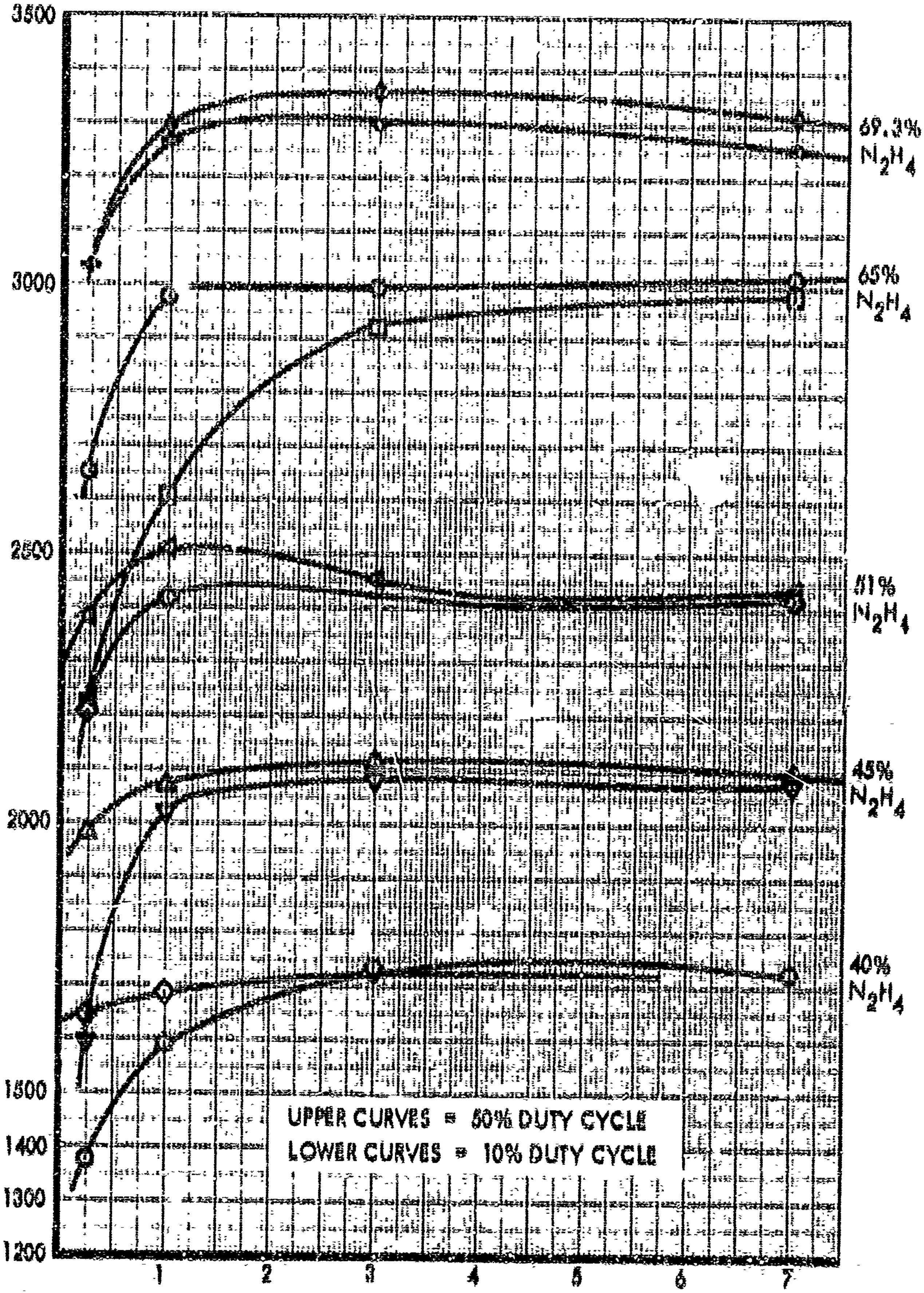

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FIGURE 39

It was not determined whether the sampling technique or the gas analysis was at fault. The results of the analyses which were run are shown in Table XIV. These results, while not quantitatively accurate, show the presence of small amounts of hydrogen in the exhaust gases of the higher temperature propellants. The absence of hydrogen in the exhaust gases of the lower temperature propellants demonstrates that these propellants are operating with no ammonia dissociation as was expected. Additionally, the recorded temperatures and measured characteristic velocities (c*) also confirm these results.

4.5 Summary and Conclusions

Thermochemical calculations have been performed over a wide range of compositions for the system hydrazine-ammonia-water. Experimental reactor firings have been conducted on seven specific monopropellants containing hydrazine, water and/or ammonia. These firings have proven that stable operation is possible over a wide range of propellant compositions. The propellant decomposition products are clean, noncorrosive gases in the temperature range of 362°F to 1,160°F. Lower temperatures have been recorded but are still questionable as to repeatability. Two of the seven monopropellants, both containing less than 40% by weight hydrazine, were shown to provide unsatisfactory operation both in steady state and pulse mode systems. The freezing points of the propellants were determined; and their densities, viscosities, and vapor pressures were measured over a wide temperature range. The ammonia and water diluents are excellent freezing point depressants for hydrazine and the propellants exhibited freezing points in the temperature range from -57°F to -130°F.

TABLE XIV

RESULTS OF EXHAUST GAS ANALYSIS

Initial Propellant Composition (Weight %)			Reported Composition* of Exhaust Gases (Weight %)			
N_2H_4	H_2O	NH_3	N_2	H_2O	NH_3	H_2
69.3	30.7	--	38.7	11.4	49.1	0.8
69.3	30.7	--	39.5	11.4	48.4	0.7
65.0	26.25	8.75	32.8	6.3	60.7	0.2
65.0	26.25	8.75	32.3	6.0	61.5	0.1
40.0	60.0	--	14.5	50.7	34.8	--
40.0	60.0	--	18.4	43.9	37.7	--
51.0	49.0	--	56.5	16.5	27.0	--
51.0	49.0	--	29.1	35.5	35.4	--
51.0	49.0	--	12.1	60.3	27.5	--
51.0	49.0	--	13.6	45.1	41.3	--

*Results are known to be in error due to sampling and/or analysis techniques. See text.

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APPENDIX

SUMMARY OF PHASE I THERMOCHEMICAL CALCULATIONS

TABLE III
THEORETICAL PERFORMANCE
HYDRAZINE - WATER SYSTEM
CHAMBER PRESSURE = 300 psia - EXHAUST PRESSURE = 14.7 psia

P_c psia	Code No.	% N_2H_4	% NH_3	% H_2O	X	Y	T_c ~ °K	T_e ~ °F	c* ft/sec	I_{sp} sec	ΔH Kcal/100gm	M.W.	Frozen Gamma (C_p/C_v)	Moles H_2	Moles N_2	Moles NH_3	Moles H_2O (Gas)	Moles H_2O (Liq-Sol)
300	3.0.40	100	—	0	0.4	—	1,255	1,980	4,395	180.6	-22.767	14.397	1.257	2.486	1.473	2.486	—	—
	3.0.60	100	—	0	0.6	—	1,102	1,487	4,309	185.7	-28.540	13.992	1.282	3.706	2.165	1.424	—	—
	3.0.80	100	—	0	0.8	—	1,038	1,392	4,160	178.4	-34.588	11.725	1.308	4.978	2.204	0.802	—	—
	3.0.100	100	—	0	1.0	—	980	1,306	3,975	170.0	-38.230	10.774	1.370	6.202	3.080	0.0169	—	—
	3.1.40	90	—	10	0.4	—	1,170	1,646	4,030	174.4	-34.703	14.852	1.248	2.247	1.485	2.247	.555	—
	3.1.60	90	—	10	0.6	—	1,017	1,370	3,902	168.4	-32.579	13.385	1.291	3.170	1.029	1.462	.545	—
	3.1.80	90	—	10	0.8	—	844	1,096	3,740	160.3	-29.529	12.149	1.325	4.483	1.434	.769	.545	—
	3.1.100	90	—	10	1.0	—	757	900	3,385	158.4	-27.180	11.459	1.385	5.395	1.720	.255	.425	—
	3.3.00	70	—	30	0.0	—	1,036	1,387	3,295	147.6	-25.135	18.348	1.207	—	.726	2.910	1.465	—
	3.3.20	70	—	30	0.2	—	865	1,136	3,303	142.7	-21.476	15.984	1.265	.374	1.039	2.330	1.463	—
	3.3.40	70	—	30	0.4	—	708	902	3,247	136.2	-20.334	15.425	1.285	1.247	1.340	1.747	1.465	—
	3.3.60	70	—	30	0.6	—	528	489	2,980	128.8	-18.100	14.278	1.326	2.620	1.402	1.165	1.465	—
	3.3.80	70	—	30	0.8	—	575	406	2,730	128.0	-16.075	13.697	1.362	3.485	1.303	.587	1.465	—
	3.3.100	70	—	30	1.0	—	589	486	2,896	124.3	-17.766	13.757	1.347	2.945	1.730	.549	1.465	—
	3.35.40	65	—	35	.4	—	539	500	2,710	106.5	-15.595	14.398	1.340	2.404	1.487	1.082	1.943	—
	3.35.80	65	—	35	.8	—	429	382	2,495	107.2	-13.596	13.257	1.356	3.265	0.758	0.561	1.890	0.045
	3.35.100	65	—	35	1.0	—	557	544	2,742	107.9	-15.573	14.570	1.334	2.237	1.495	1.164	1.962	—
	3.4.00	60	—	40	0.0	—	773	922	2,922	126.3	-18.325	18.725	1.242	—	.428	2.485	2.230	—
	3.4.20	60	—	40	0.2	—	654	717	2,776	119.6	-16.408	17.104	1.282	.249	.824	1.967	2.230	—
	3.4.40	60	—	40	0.4	—	534	500	2,589	115.5	-14.280	15.775	1.323	1.488	1.323	1.488	2.230	—
	3.4.60	60	—	40	0.6	—	437	337	2,463	108.9	-12.398	14.423	1.332	2.247	1.373	.998	2.330	.100
	3.4.80	60	—	40	0.8	—	425	366	2,405	104.3	-12.506	12.438	1.274	2.986	1.422	.409	1.597	.462
	3.4.100	60	—	40	1.0	—	539	475	2,582	110.7	-13.967	15.495	1.328	1.595	1.258	1.433	2.232	—
	3.45.00	55	—	45	0	—	645	700	2,482	114.4	-15.050	18.443	1.267	—	0.572	2.288	2.498	—
	3.45.20	55	—	45	.2	—	500	406	2,480	107.0	-15.152	17.195	1.308	0.486	0.853	1.522	2.478	—
	3.45.40	55	—	45	.4	—	446	343	2,337	100.3	-11.187	15.940	1.311	1.373	1.038	1.375	2.255	0.343

TABLE III (Cont'd)
THEORETICAL PERFORMANCE
HYDRAZINE – WATER SYSTEM
CHAMBER PRESSURE = 300 psia – EXHAUST PRESSURE = 14.7 psia

P_c psia	Code No.	$\%N_2H_4$	$\%NH_3$	$\%H_2O$	x	y	T_c — °K	T_c — °F	c^* ft/sec	I_{sp} sec	ΔH_f Kcal/100gm	M.W.	Frozen Gamma (Ch.)	Moles H_2	Moles N_2	Moles NH_3	Moles H_2O (Gas)	Moles H_2O (Liquid)
300	31,45,60	55	—	45	.6	—	425	304	2,329	101.3	-11.787	14.857	1.258	2.159	1.289	0.915	1.824	0.574
	31,45,80	55	—	45	.8	—	425	302	2,312	100.1	-11.740	13.953	1.222	2.746	1.457	0.458	1.325	1.073
	31,45,100	55	—	45	1.0	—	481	407	2,307	100.3	-12.204	16.625	1.222	0.986	0.566	1.623	2.420	—
	31,5,00	50	—	50	0.0	—	470	406	2,380	99.4	-11.346	18.623	1.318	—	.520	2.080	2.775	—
	31,5,20	50	—	50	0.2	—	452	355	2,243	97.4	-10.895	17.266	1.249	.404	.728	1.664	2.408	.251
	31,5,40	50	—	50	0.4	—	440	336	2,232	97.5	-10.930	16.017	1.227	1.208	.936	1.248	1.936	.259
	31,5,60	50	—	50	0.6	—	432	307	2,208	97.4	-10.900	15.097	1.195	1.672	1.144	0.832	1.494	1.300
	31,5,80	50	—	50	0.8	—	419	295	2,195	96.6	-10.759	14.205	1.177	2.456	1.352	0.416	1.063	1.702
	31,5,100	50	—	50	1.0	—	407	336	2,247	97.5	-10.577	17.311	1.224	0.402	0.720	1.679	2.467	0.309
	31,45,00	45	—	55	0	—	457	344	2,143	95.7	-10.082	18.562	1.225	—	0.468	1.872	2.437	0.475
	.20	45	—	55	.2	—	430	351	2,128	93.5	-10.050	17.338	1.190	0.562	0.655	1.402	1.994	1.058
	.40	45	—	55	.4	—	440	333	2,109	93.1	-9.956	16.281	1.170	1.123	0.842	1.125	1.572	1.481
	.60	45	—	55	.6	—	428	312	2,106	92.4	-9.807	15.368	1.156	1.685	1.030	0.749	1.177	1.876
	.80	45	—	55	.8	—	414	286	2,062	91.6	-9.442	14.512	1.140	2.247	1.217	0.374	0.804	2.238
	.100	45	—	55	1.0	—	431	302	2,129	92.5	-10.056	17.438	1.186	0.562	0.609	1.501	2.032	1.020
	31,40,60	40	—	60	0	—	456	361	1,986	88.4	-8.950	18.402	1.194	—	0.416	1.664	1.918	1.402
	.20	40	—	60	.2	—	447	345	1,978	87.9	-8.885	17.431	1.159	0.499	0.582	1.331	1.554	1.774
	.40	40	—	60	.4	—	436	325	1,957	87.2	-8.744	16.458	1.137	0.999	0.749	0.998	1.202	2.128
	.60	40	—	60	.6	—	422	302	1,936	86.5	-8.512	15.423	1.118	1.498	0.915	0.666	0.837	2.454
	.80	40	—	60	.8	—	408	275	1,925	85.4	-8.439	14.333	1.112	1.997	1.083	0.333	0.586	2.744
	.100	40	—	60	1.0	—	448	347	1,982	88.0	-8.906	17.586	1.149	0.428	0.557	1.342	1.610	1.722
	31,70,00	30	—	70	0.0	—	445	343	1,672	72.9	-6.104	18.368	1.073	—	0.312	1.248	0.567	2.908
	.20	30	—	70	.2	—	436	328	1,680	72.4	-6.022	17.535	1.070	0.373	0.437	0.998	0.741	3.144
	.40	30	—	70	.4	—	425	298	1,591	72.0	-5.936	16.803	1.068	0.748	0.563	0.749	0.539	3.347
	.100	30	—	70	1.0	—	438	329	1,604	72.5	-6.048	17.808	1.071	0.246	0.364	1.094	0.857	3.089

TABLE III (Cont'd)
THEORETICAL PERFORMANCE
HYDRAZINE - WATER SYSTEM
CHAMBER PRESSURE = 300 psia - EXHAUST PRESSURE = 14.7 psia

P_c psi	Code No.	% N_2H_4	% NH_3	% H_2O	X	Y	T_c — °F	T_e — °F	c^* ft/sec	I_{sp} sec	ΔH_f Kcal/100gm	M.W.	Frozen Gamma (Ch.)	Moles H_2	Moles N_2	Moles NH_3	Moles H_2O (Gas)	Moles H_2O (Liquid)
1000	11.1.1000	100	—	0	1.0	—	3678	1,829	3,962	140.7	−31.252	10.786	1.373	6.307	3.106	0.625	—	—
6000	4.1.1000	100	—	0	1.0	—	3903	1,648	3,980	159.7	−37.942	10.865	1.367	6.031	3.050	0.540	—	—
10,000	1.1.1000	100	—	0	1.0	—	3925	1,170	4,089	189.8	−42.107	10.922	1.362	5.933	3.546	0.265	—	—
1000	31.1.1000	90	—	10	1.0	—	2734	882	3,540	129.6	−19.298	11.257	1.371	5.469	2.759	0.585	0.551	—
	31.2.1000	70	—	30	1.0	—	5967	530	2,825	103.2	−12.242	13.412	1.352	3.207	1.820	0.748	1.145	—
	31.4.1000	60	—	40	1.0	—	4865	425	2,503	91.4	−9.402	15.275	1.336	1.859	1.227	1.290	2.332	—
	31.50.1000	50	—	50	1.0	—	4912	208	2,056	79.0	−7.578	17.425	1.322	0.585	0.702	1.707	7.240	0.225
6000	31.1.1000	90	—	10	1.0	—	7278	962	3,428	114.9	−16.236	11.532	1.259	5.132	2.667	0.313	0.555	—
	31.3.1000	70	—	30	1.0	—	5765	649	2,942	134.8	−20.872	13.996	1.319	2.739	1.640	1.079	1.485	—
	31.4.1000	60	—	40	1.0	—	5403	516	2,478	109.6	−16.445	15.848	1.331	1.458	1.109	1.527	2.232	—
	31.50.1000	50	—	50	1.0	—	4864	402	2,249	107.7	−13.224	17.337	1.265	0.640	0.722	1.451	2.340	0.522
10,000	31.1.1000	90	—	10	1.0	—	7798	977	3,467	172.3	−34.138	11.483	1.354	4.986	2.591	0.423	0.555	—
	31.3.1000	70	—	30	1.0	—	6337	680	2,937	145.5	−22.504	14.107	1.326	2.494	1.597	1.169	1.640	—
	31.4.1000	60	—	40	1.0	—	5598	546	2,630	125.6	−18.028	16.029	1.305	1.307	1.012	1.576	2.220	—
	31.50.1000	50	—	50	1.0	—	5210	457	2,226	114.9	−15.162	17.183	1.222	0.578	0.745	1.429	2.345	0.739

TABLE III
THEORETICAL PERFORMANCE
HYDRAZINE - AMMONIA SYSTEM
CHAMBER PRESSURE = 300 psia - EXHAUST PRESSURE = 14.7 psia

P_c psia	Code No.	$\%N_2H_4$	$\%NH_3$	$\%H_2O$	x	w	T_c — °K	T_c — °F	c*	I_{sp}	ΔH_f	av. M.W.	Frozen Gamma (Ch.)	Moles H_2	Moles N_2	Moles NH_3	Moles H_2O (Gas)	Moles H_2O (Liquid)
300	4.95.10.0	95	5	—	1.0	0	810	999	3,778	162.4	-30.296	20.886	1.387	5.929	2.964	0.254	—	—
	4.90.0.0	90	10	—	0	0	1,500	2,240	4,743	182.2	-36.054	11.908	1.264	—	0.926	4.237	—	—
	.2.0	—	—	—	.2	0	1,258	1,804	4,646	182.0	-35.064	16.621	1.199	1.103	1.301	3.503	—	—
	.4.0	90	10	—	.4	0	1,213	1,724	4,529	179.1	-36.253	14.720	1.236	2.247	1.605	2.834	—	—
	.4.25	90	10	—	.4	.25	1,073	1,472	4,474	178.2	-36.501	14.467	1.244	2.467	1.758	2.467	—	—
	.4.50	90	10	—	.4	.50	1,055	1,440	4,098	177.3	-36.115	14.166	1.251	2.657	1.828	2.540	—	—
	.6.0	90	10	—	.6	0	1,066	1,460	4,032	173.8	-34.715	13.308	1.276	3.370	2.059	2.025	—	—
	.6.25	90	10	—	.6	.25	1,037	1,408	4,047	172.5	-34.225	13.053	1.284	3.590	2.133	1.938	—	—
	.6.50	90	10	—	.6	.50	1,008	1,356	3,979	171.2	-33.448	12.808	1.293	3.872	2.208	1.771	—	—
	.8.0	90	10	—	.8	0	979	1,305	3,880	166.5	-30.857	12.102	1.319	4.493	2.438	1.336	—	—
	.8.25	90	10	—	.8	.25	901	1,163	3,845	164.8	-31.422	11.896	1.327	4.783	2.507	1.139	—	—
	.8.50	90	10	—	.8	.50	862	1,092	3,907	163.2	-30.590	11.487	1.325	4.934	2.388	1.042	—	—
	.10.0	90	10	—	1.0	0	774	932	3,679	157.5	-28.307	11.096	1.360	5.457	2.802	0.587	—	—
	.10.25	90	10	—	1.0	.25	745	882	3,634	155.5	-27.97[illegible]	10.919	1.368	5.337	2.802	0.440	—	—
	.10.50	90	10	—	1.0	.50	712	822	3,588	153.5	-27.046	10.746	1.375	5.057	2.955	0.256	—	—
	4.90.10.10	90	10	—	1.0	1.0	729	852	3,607	154.4	-27.380	10.895	1.372	5.352	2.925	0.252	—	—
	4.80.0.0	80	20	—	0	0	1,325	1,925	3,976	172.2	-24.027	18.245	1.670	—	0.852	4.923	—	—
	.10.25	80	20	—	1.0	.25	476	397	3,191	138.7	-23.230	11.700	1.367	5.403	2.957	0.888	—	—
	.10.50	80	20	—	1.0	.5	579	582	3,198	136.5	-23.457	12.411	1.379	5.873	2.790	0.587	—	—
	4.70.0.0	70	30	—	0	0	1,319	1,915	3,469	160.9	-29.740	18.572	1.178	—	0.728	4.674	—	—
	.2.0	70	30	—	.2	0	1,044	1,420	3,405	158.3	-28.802	16.771	1.208	0.874	1.167	4.077	—	—
	.4.0	70	30	—	.4	0	932	1,216	3,559	156.0	-27.267	15.228	1.240	1.747	1.317	3.309	—	—
	.4.25	70	30	—	.4	.25	846	1,063	3,473	149.7	-25.756	14.271	1.265	2.408	1.580	3.048	—	—
	.4.50	70	30	—	.4	.5	757	902	3,304	146.6	-24.027	13.408	1.293	3.088	1.751	2.420	—	—
	.6.0	70	30	—	.6	0	876	1,118	3,441	148.1	-25.207	13.962	1.274	2.620	1.602	2.926	—	—
	.6.25	70	30	—	.6	.25	728	850	3,306	142.7	-23.420	13.675	1.302	3.282	1.802	2.486	—	—
	.6.50	70	30	—	.6	.5	642	695	3,185	138.7	-23.465	12.456	1.338	3.942	2.040	2.048	—	—

TABLE VIII (Cont'd)

THEORETICAL PERFORMANCE

HYDRAZINE – AMMONIA SYSTEM

CHAMBER PRESSURE = 300 psia – EXHAUST PRESSURE = 14.7 psia

P_c psi	Code No.	$\%N_2H_4$	$\%NH_3$	$\%H_2O$	X	Y	T_c — °K	T_c — °F	c*	I_{sp}	ΔH_R	M.W.	Frozen Gamma (Ch.)	Moles H_2	Moles N_2	Moles NH_3	Moles H_2O (Gas)	Moles H_2O (Liquid)
300	.8,0	70	30	—	.8	0	700	801	3,263	140.9	-22,104	12.504	1.381	3.496	1.873	2.343	—	—
	.8,25	70	30	—	.8	.25	614	645	3,136	136.5	-20,106	13.287	1.339	4.325	2.270	1.904	—	—
	.8,50	70	30	—	.8	.5	529	492	2,974	127.5	-18,692	11.617	1.363	4.216	2.333	1.463	—	—
	.10,0	70	30	—	1.0	0	586	596	3,086	132.4	-20,104	12.008	1.347	4.388	2.084	1.762	—	—
	.10,25	70	30	—	1.0	.25	502	445	2,916	125.8	-17,990	11.403	1.369	5.027	2.404	1.129	—	—
	.10,50	70	30	—	1.0	.5	422	301	2,736	110.8	-15,789	10.876	1.382	5.489	2.625	0.880	—	—
	4,30,10,10	70	30	—	1.0	1.0	596	596	3,086	132.4	-20,263	12.029	1.347	4.367	2.104	1.752	—	—
	4,45,8,25	55	45	—	.8	.25	396	253	2,489	106.7	-10,180	12.570	1.298	3.737	1.848	2.459	—	—
	.8,50	55	45	—	.8	.5	277	039	2,549	92.1	-9,750	11.565	1.379	4.727	2.148	1.779	—	—
	4,4,0,0	60	40	—	0	0	937	1,227	3,395	148.3	-25,288	18.285	1.189	—	0.404	4.865	—	—
	.2,0	60	40	—	.2	0	866	1,109	3,305	144.8	-24,098	16.756	1.237	0.749	0.874	4.365	—	—
	.4,0	60	40	—	.4	0	788	959	3,120	139.9	-22,488	15.462	1.268	1.495	1.123	3.866	—	—
	.4,25	60	40	—	.4	.25	669	745	3,082	132.6	-20,199	14.775	1.288	2.378	1.427	3.259	—	—
	.4,50	60	40	—	.4	.5	578	582	2,880	123.8	-17,485	13.066	1.329	3.259	1.770	2.672	—	—
	.6,0	60	40	—	.6	0	687	777	3,109	132.8	-20,563	14.354	1.282	2.247	1.373	3.367	—	—
	.6,25	60	40	—	.6	.25	568	563	2,912	125.2	-18,019	13.238	1.326	3.327	1.666	2.730	—	—
	.6,50	60	40	—	.6	.5	458	365	2,662	115.5	-15,236	12.284	1.355	4.366	1.960	2.108	—	—
	.8,0	60	40	—	.8	0	586	595	2,940	128.4	-18,489	13.394	1.308	2.996	1.623	2.848	—	—
	.8,25	60	40	—	.8	.25	470	386	2,718	116.7	-15,853	12.438	1.352	3.876	1.916	2.263	—	—
	.8,50	60	40	—	.8	.5	363	194	2,459	105.3	-12,737	11.574	1.364	4.757	2.210	1.674	—	—
	.10,25	60	40	—	1.0	.25	376	2..	2,502	107.3	-13,112	11.653	1.363	4.626	2.1..	1.753	—	—
	.10,50	60	40	—	1.0	.5	275	035	2,195	94.0	-10,145	10.942	1.398	5.506	2.459	1.074	—	—
	.10,10	60	40	—	1.0	1.0	543	537	2,865	121.8	-17,401	13.018	1.32	3.257	1.730	2.422	—	—
	4,5,0,0	50	50	—	0	0	802	988	3,077	133.7	-20,548	18.244	1.207	—	0.530	5.206	—	—
	.2,0	50	50	—	.2	0	724	844	2,981	129.3	-19,223	16.803	1.235	0.634	0.728	4.680	—	—
	.4,0	50	50	—	.4	0	638	689	2,875	124.0	-17,667	15.724	1.267	1.268	0.936	4.106	—	—
	.4,25	50	50	—	.4	.25	484	412	2,608	112.4	-14,574	14.388	1.323	2.349	1.303	3.450	—	—

TABLE III (Cont'd)

THEORETICAL PERFORMANCE

HYDRAZINE – AMMONIA SYSTEM

CHAMBER PRESSURE = 300 psia – EXHAUST PRESSURE = 14.7 psia

P_c psi	Code No.	% N_2H_4	% NH_3	% H_2O	X	Y	T_c ~ °K	T_c ~ °F	c*	I_{sp}	ΔH_R	M.W.	Frozen Gamma (C_p/C_v)	Moles H_2	Moles N_2	Moles NH_3	Moles H_2O (Gas)	Moles H_2O (Liquid)
300	.4.50	50	50	—	.4	.5	340	152	2,281	97.9	-11,805	12,762	1.342	3.451	1.678	2.716	—	—
	.4.0	50	50	—	.5	0	550	530	2,733	117.8	-15,905	14,740	1.300	1.872	1.044	3.748	—	—
	.6.25	50	50	—	.4	.25	400	261	2,436	104.5	-12,338	13,302	1.328	2.343	1.511	3.024	—	—
	.4.50	50	50	—	.6	.5	364	205	2,052	88.0	-8,910	12,518	1.371	4.078	1.578	2.302	—	—
	.8.0	50	50	—	.8	0	464	375	2,570	110.6	-14,542	13,889	1.308	2.496	1.252	3.257	—	—
	.8.25	50	50	—	.8	.25	322	120	2,227	95.7	-10,346	12,654	1.348	3.557	1.729	2.418	—	—
	.10.0	50	50	—	1.0	0	382	227	2,392	102.5	-12,083	13,130	1.338	3.030	1.589	2.932	—	—
	.4.4.0.0	40	60	—	0	0	622	659	2,682	116.0	-15,470	17,848	1.260	—	0.476	5.187	—	—
	.2.0	40	60	—	.2	0	548	527	2,571	111.3	-14,157	16,367	1.270	0.477	0.582	4.856	—	—
	.4.0	40	60	—	.4	0	473	395	2,445	105.4	-12,815	15,952	1.268	0.999	0.740	4.525	—	—
	.6.0	40	60	—	.6	0	402	266	2,307	99.3	-11,323	15,485	1.281	1.463	0.916	4.186	—	—
	.8.0	40	60	—	.8	0	336	145	2,145	92.2	-9,734	14,425	1.305	1.957	1.082	3.856	—	—
	.10.0	40	60	—	1.0	0	276	037	1,959	84.2	-8,147	13,787	1.351	2.486	1.288	3.525	—	—
	4.35.6.0	35	65	—	.4	0	302	084	1,958	84.0	-7,929	17,429	1.292	4.369	0.208	4.399	—	—
	4.70.0.0	30	70	—	0	0	460	368	2,173	92.8	-10,322	17,636	1.282	—	0.312	5.358	—	—
	.2.0	30	70	—	.2	0	385	239	2,062	88.7	-9,133	16,873	1.283	0.374	0.437	5.108	—	—
	.4.0	30	70	—	.4	0	312	084	1,922	82.9	-7,862	16,209	1.300	0.740	0.562	4.859	—	—
1000	4.90.10.10	90	10	—	1.0	1.0	697	796	3,528	128.8	-19,369	10,403	1.380	5.208	3.027	0.186	—	—
	4.70.30.10	70	30	—	1.0	1.0	593	608	3,082	125.4	-13,916	11,738	1.259	4.308	2.287	1.535	—	—
	4.60.40.10	60	40	—	1.0	1.0	523	480	2,787	120.8	-11,914	12,498	1.344	3.427	1.820	2.432	—	—
4000	4.90.10.10	90	10	—	1.0	1.0	755	903	3,680	158.3	-30,786	10,980	1.365	5.760	2.856	0.481	—	—
	4.70.30.10	70	30	—	1.0	1.0	627	668	3,142	143.7	-23,729	12,260	1.309	4.332	2.335	1.959	—	—
	4.60.40.10	60	40	—	1.0	1.0	570	567	2,955	130.7	-20,558	11,258	1.323	3.114	1.462	2.160	—	—
2,000	4.90.10.10	90	10	—	1.0	1.0	734	862	3,486	154.0	-34,854	11,334	1.337	3.568	2.797	0.409	—	—
	4.70.30.10	70	30	—	1.0	1.0	643	696	3,188	139.1	-26,308	12,646	1.300	3.349	2.046	2.041	—	—
	4.60.40.10	60	40	—	1.0	1.0	595	625	2,958	142.6	-22,735	12,462	1.336	2.956	1.409	2.874	—	—

TABLE XV

THEORETICAL PERFORMANCE

HYDRAZINE – EQUAL WEIGHT PERCENT WATER – AMMONIA SYSTEM

P_c psi	Code No.	$\%N_2H_4$	$\%NH_3$	$\%H_2O$	X	Y	T_c — °K	T_c — °F	c*	I_{sp}	ΔH_R	M.W.	Frozen Gamma (γ_e)	Moles H_2	Moles N_2	Moles NH_3	Moles H_2O (Gas)	Moles H_2O (Liquid)
300	7.8.1.0.0	80	10	10	0	0	1,289	1,858	3,805	168.2	−32.564	18.889	1.179	—	0.882	3.966	0.555	—
	.2.0	80	10	10	.2	0	1,196	1,682	3,872	166.0	−31.683	16.755	1.202	0.996	1.185	3.250	0.555	—
	.4.0	80	10	10	.4	0	1,083	1,390	3,736	162.6	−29.594	15.074	1.239	1.950	1.484	2.581	0.555	—
	.4.25	80	10	10	.4	.25	991	1,324	3,712	160.2	−29.530	14.745	1.258	2.207	1.578	2.437	0.555	—
	.4.5	80	10	10	.4	.5	960	1,270	3,685	158.9	−27.035	14.425	1.266	2.437	1.845	2.295	0.555	—
	.6.0	80	10	10	.6	0	885	1,133	3,407	155.1	−27.657	13.730	1.287	2.795	1.830	1.839	0.555	—
	.6.25	80	10	10	.6	.25	825	1,079	3,572	153.5	−27.072	13.429	1.278	3.256	1.900	1.772	0.555	—
	.6.5	80	10	10	.6	.5	803	1,025	3,538	159.7	−26.462	13.170	1.307	3.436	1.997	1.625	0.555	—
	.8.0	80	10	10	.8	0	749	889	3,429	147.0	−24.842	12.555	1.329	3.786	2.082	1.258	0.555	—
	.8.25	80	10	10	.8	.25	719	825	3,384	145.0	−26.575	12.327	1.322	4.236	2.237	1.026	0.555	—
	.8.5	80	10	10	.8	.5	690	782	3,336	143.0	−25.464	12.708	1.347	4.404	2.310	0.959	0.555	—
	.10.0	80	10	10	1.0	0	674	650	3,208	137.4	−23.742	11.581	1.357	4.772	2.466	0.587	0.555	—
	.10.25	80	10	10	1.0	.25	588	598	3,105	135.1	−20.991	11.253	1.374	5.232	2.573	0.440	0.555	—
	.10.5	80	10	10	1.0	.5	527	[illegible]	3,100	132.8	−20.240	11.325	1.392	5.422	2.542	0.274	0.555	—
	7.80.10.10.10	80	10	10	1.0	1.0	647	716	3,203	139.3	−22.463	11.652	1.358	4.745	2.404	0.752	0.555	—
	7.70.15.0.0	70	15	15	0	0	1,086	1,495	3,520	153.8	−27.380	16.679	1.172	—	0.738	3.792	0.833	—
	.2.0	70	15	15	.2	0	985	1,313	3,458	152.1	−25.876	14.896	1.226	0.574	1.029	3.240	0.833	—
	.4.0	70	15	15	.4	0	942	1,237	3,350	150.3	−23.993	15.342	1.262	1.747	1.378	2.628	0.833	—
	.4.25	70	15	15	.4	.25	896	973	3,287	148.0	−20.857	14.840	1.276	2.092	1.471	2.408	0.833	—
	.4.5	70	15	15	.4	.5	749	889	3,232	147.2	−22.272	14.370	1.290	2.408	1.530	2.194	0.833	—
	.6.0	70	15	15	.6	0	719	836	3,157	137.3	−20.476	14.082	1.300	2.620	1.462	2.046	0.833	—
	.6.25	70	15	15	.6	.25	653	752	3,127	136.2	−20.730	13.457	1.316	2.957	1.772	1.825	0.833	—
	.6.5	70	15	15	.6	.5	537	693	3,052	135.0	−19.728	13.260	1.330	3.282	1.802	[illegible]	0.833	—
	.8.0	70	15	15	.8	0	567	617	3,004	138.6	−19.089	13.075	1.339	3.475	1.853	1.301	0.833	—
	.8.25	70	15	15	.8	.25	553	535	2,918	125.2	−18.024	12.652	1.352	3.825	2.053	1.241	0.833	—
	.8.5	70	15	15	.8	.5	508	455	2,820	121.5	−16.955	12.357	1.364	[illegible]	2.313	1.023	0.833	—
	.10.0	70	15	15	1.0	0	482	405	2,773	118.9	−16.253	12.098	1.367	4.368	2.324	0.983	0.833	—
	.10.25	70	15	15	1.0	.25	438	328	2,680	114.0	−15.251	[illegible]	1.376	4.597	2.394	0.445	0.833	—

TABLE D? (Cont'd)

THEORETICAL PERFORMANCE

HYDRAZINE – EQUAL WEIGHT PERCENT WATER – AMMONIA SYSTEM

P_c psia	Code No.	Wt% N_2H_4	Wt% NH_3	Wt% H_2O	X	Y	T_c — °K	T_e — °F	c^*	I_{sp}	ΔH_R	M.W.	Frozen Gamma (C_p/C_v)	Moles H_2	Moles N_2	Moles NH_3	Moles H_2O (Gas)	Moles H_2O (Liquid)
300	.10,.5	70	15	15	1.0	.5	397	254	2,582	117.5	-14,103	11.486	1.319	5.029	2.404	0.440	0.833	—
	.10,1.0	70	15	15	1.0	1.0	594	591	2,975	137.7	-18,743	12.902	1.344	3.956	1.937	1.396	0.830	—
	.20,.10,.10,.25	64	18	18	1.0	.25	390	244	2,393	107.1	-13,186	12.032	1.332	4.390	2.125	0.793	0.752	0.257
	.10,.5	64	18	18	1.0	.5	379	272	2,470	106.5	-13,039	11.481	1.310	4.787	2.348	0.525	0.430	0.579
	7,20,20,0,0	60	20	20	0	0	974	1,102	3,152	136.9	-21,549	16.571	1.254	—	0.626	3.650	1.110	—
	.2,0	60	20	20	.2	0	765	719	3,030	133.7	-19,944	16.535	1.267	0.749	0.874	3.171	1.110	—
	.4,0	60	20	20	.4	0	655	720	2,708	125.1	-18,097	15.437	1.285	1.498	1.123	2.672	1.110	—
	.4,.25	60	20	20	.4	.25	590	603	2,704	120.7	-16,752	14.972	1.308	1.938	1.270	2.378	1.110	—
	.4,.5	60	20	20	.4	.5	526	488	2,592	115.9	-15,428	14.326	1.330	2.378	1.417	2.085	1.110	—
	.6,0	60	20	20	.6	0	565	520	2,728	117.4	-15,822	14.468	1.324	2.247	1.373	2.173	1.110	—
	.6,.25	60	20	20	.6	.25	532	406	2,630	112.2	-14,467	13.896	1.342	2.687	1.520	1.879	1.110	—
	.6,.5	60	20	20	.6	.5	437	298	2,484	106.4	-13,135	13.252	1.352	3.127	1.666	1.585	1.110	—
	.8,0	60	20	20	.8	0	439	325	2,522	108.3	-13,483	13.510	1.338	2.996	1.623	1.674	1.110	—
	.8,.25	60	20	20	.8	.25	403	286	2,452	105.3	-12,747	12.965	1.332	3.436	1.769	1.380	0.963	0.147
	.8,.50	60	20	20	.8	.5	392	265	2,445	105.0	-12,675	12.539	1.327	3.876	1.916	1.086	0.683	0.427
	.10,0	60	20	20	1.0	0	395	252	2,440	105.2	-12,738	12.457	1.315	3.745	1.872	1.174	0.763	0.347
	7,23,23,.6,.25	54	23	23	.6	.25	408	275	2,366	102.6	-11,998	14.040	1.306	2.538	1.404	1.719	1.007	0.270
	.6,.5	54	23	23	.6	.5	395	251	2,349	101.7	-11,864	13.407	1.275	3.232	1.573	1.374	0.679	0.597
	7,24,24,.4,.25	52	24	24	.4	.25	405	254	2,347	101.0	-11,709	15.008	1.336	1.826	1.150	2.255	1.303	0.029
	.4,.50	52	24	24	.4	.50	407	272	2,335	100.8	-11,578	14.254	1.287	2.265	1.308	2.003	0.936	0.396
	7,25,25,0,0	50	25	25	0	0	644	720	2,487	116.3	-15,485	18.339	1.252	—	0.530	3.540	1.388	—
	.2,0	50	25	25	.2	0	547	526	2,503	107.7	-13,939	17.020	1.289	0.404	0.738	3.122	1.388	—
	.4,0	50	25	25	.4	0	450	380	2,372	102.2	-12,085	15.904	1.289	1.309	0.775	2.736	1.388	—
	.6,0	50	25	25	.6	0	403	283	2,311	99.9	-11,446	14.957	1.289	1.873	1.144	2.300	1.254	0.134
	7,28,28,.4,0	44	28	28	.4	0	475	307	2,272	96.2	-10,657	14.088	1.257	1.696	0.826	2.749	1.022	0.324

TABLE IV (Cont'd)

THEORETICAL PERFORMANCE

HYDRAZINE – EQUAL WEIGHT PERCENT WATER – AMMONIA SYSTEM

P_c psi	Code No.	% N_2H_4	% NH_3	% H_2O	X	Y	T_c — °K	T_c — °F	c*	I_{sp}	ΔH_R	m.w.	Frozen Gamma (Ch. J)	Moles N_2	Moles H_2	Moles NH_3	Moles H_2O (Gas)	Moles H_2O (Liquid)
300	7,30,30,0,0	40	30	30	0	0	401	276	2,259	90.7	-30,082	18,159	1.282	0.0021	0.424	3.406	1.408	0.287
	.2.2	40	30	30	.2	0	400	1?6	2,140	90.5	-30,098	17,724	1.278	0.497	0.382	3.496	1.060	0.625
300	7,10,10,10,30	80	10	10	1.0	1.0	425	626	3,187	136.4	-25,392	11,583	1.389	5.064	2.396	0.540	0.1.35	—
	7,05,05,50,30	70	15	15	1.0	1.0	362	576	2,887	120.2	-32,674	12,972	1.355	3.962	2.039	1.090	0.802	—
	7,20,20,10,10	60	20	20	1.0	1.0	472	437	2,607	95.7	-33,386	13,794	1.189	2.452	1.485	1.577	1.130	—
600	7,10,10,10,30	80	10	10	1.0	1.0	677	768	3,304	151.3	-26,297	12,027	1.330	4.518	2.200	0.956	0.525	—
	7,15,15,10,10	70	15	15	1.0	1.0	620	643	3,027	138.5	-30,067	13,146	1.335	3.385	1.857	1.528	0.930	—
	7,20,20,10,10	60	20	20	1.0	1.0	558	518	2,798	126.0	-32,286	14,574	1.321	2.385	1.300	2.254	1.170	—
1,000	7,10,10,10,70	80	10	10	1.0	1.0	701	803	3,294	158.8	-28,982	12,264	1.343	4.307	2.278	1.024	0.515	—
	7,15,15,15,30	70	15	15	2.0	1.0	625	689	3,065	145.6	-28,322	13,331	1.308	3.222	1.802	1.665	0.900	—
	7,20,20,10,10	60	20	20	1.0	1.0	573	572	2,727	132.4	-30,152	14,763	1.304	2.058	1.309	2.380	1.150	—

HYDRAZINE - AMMONIA SYSTEM

CHAMBER TEMPERATURE VS % NH_3 FOR VARYING AMMONIA DISSOCIATION

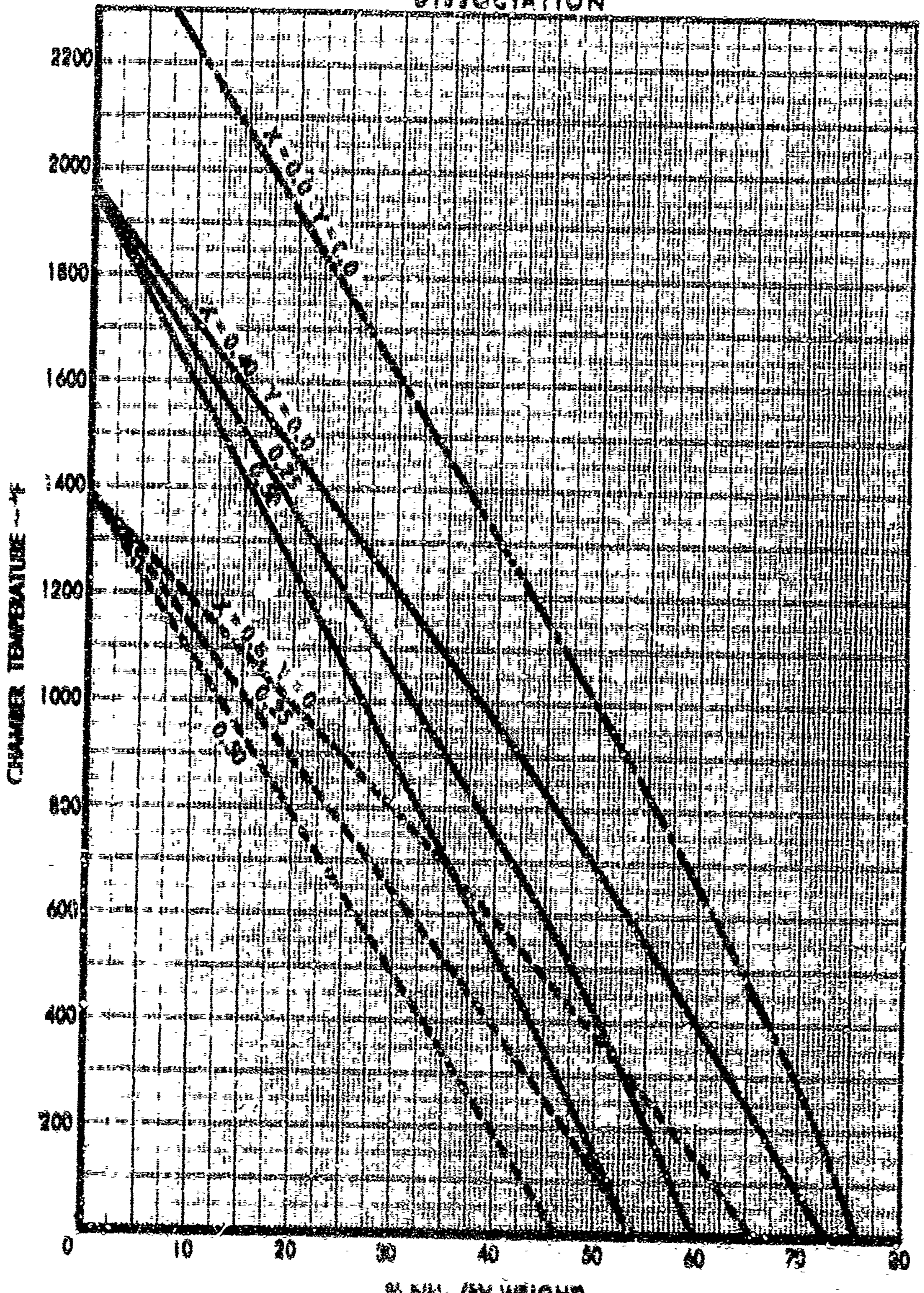


FIGURE 4

HYDRAZINE - AMMONIA SYSTEM

CHAMBER TEMPERATURE VS % NH_3 FOR VARYING AMMONIA DISSOCIATION

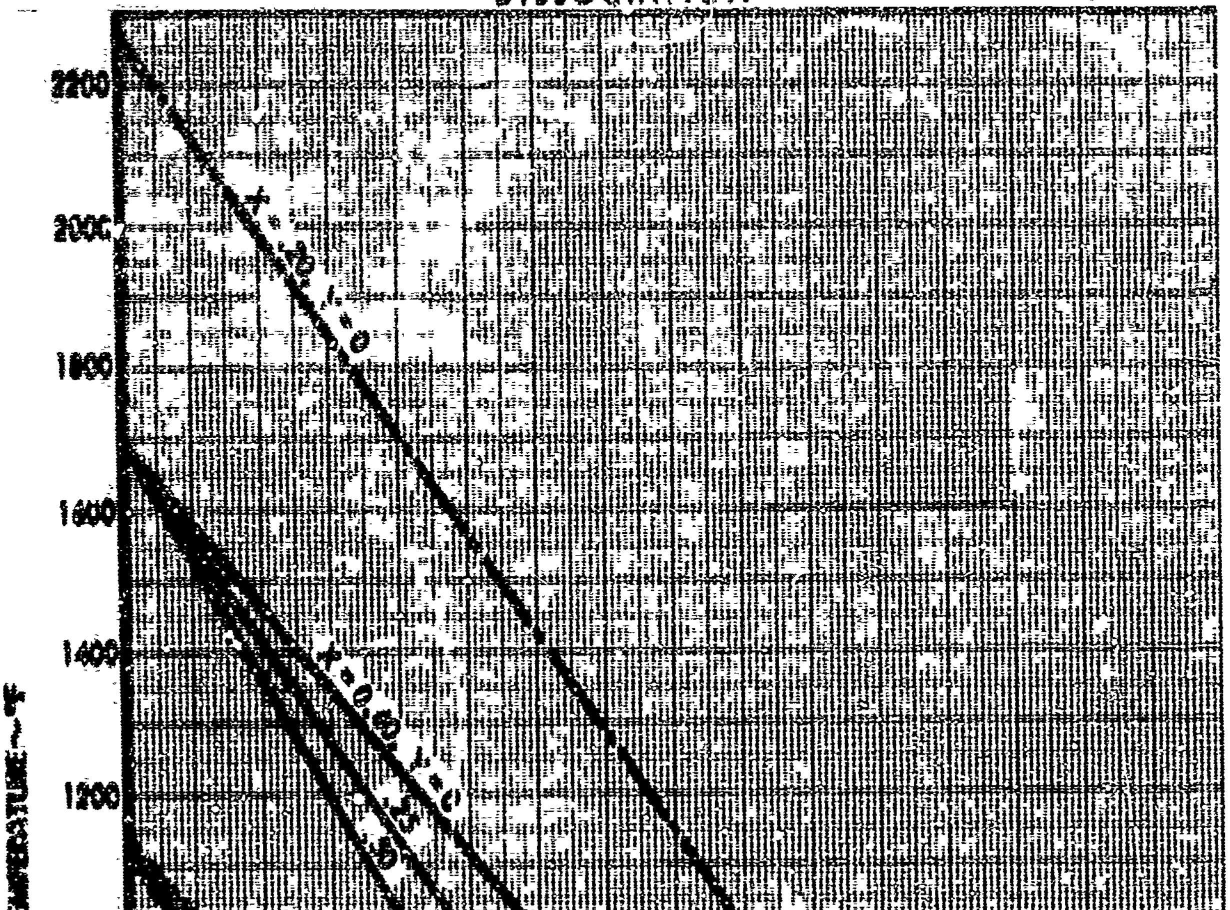
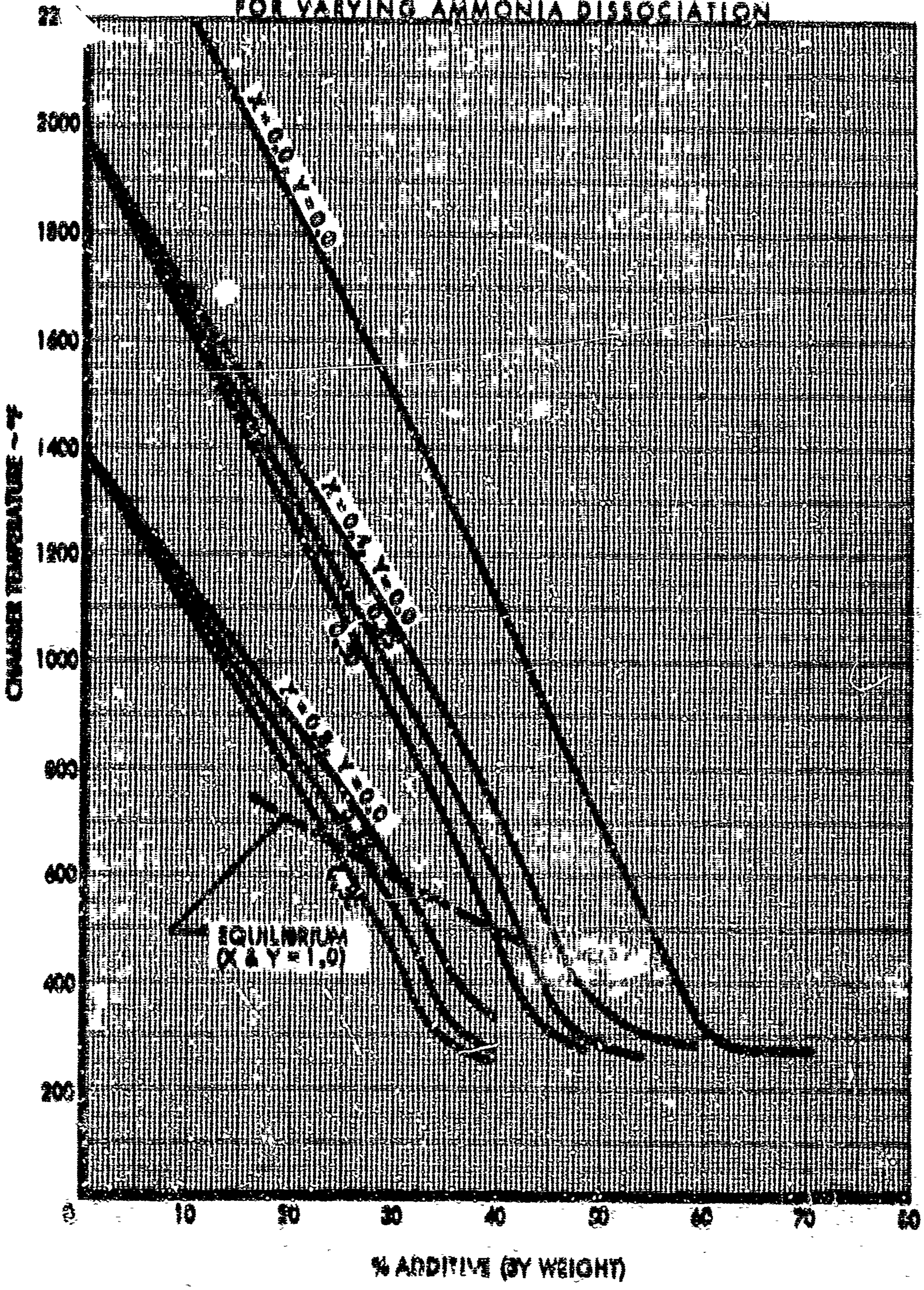


FIGURE 5

31046

HYDRAZINE - EQUAL WEIGHT % H_2O AND NH_3 SYSTEM
CHAMBER TEMPERATURE VS % ADDITIVE
FOR VARYING AMMONIA DISSOCIATION



51043

FIGURE 6

HYDRAZINE - EQUAL WEIGHT % H_2O AND NH_3 SYSTEM
CHAMBER TEMPERATURE VS % ADDITIVE
FOR VARYING AMMONIA DISSOCIATION

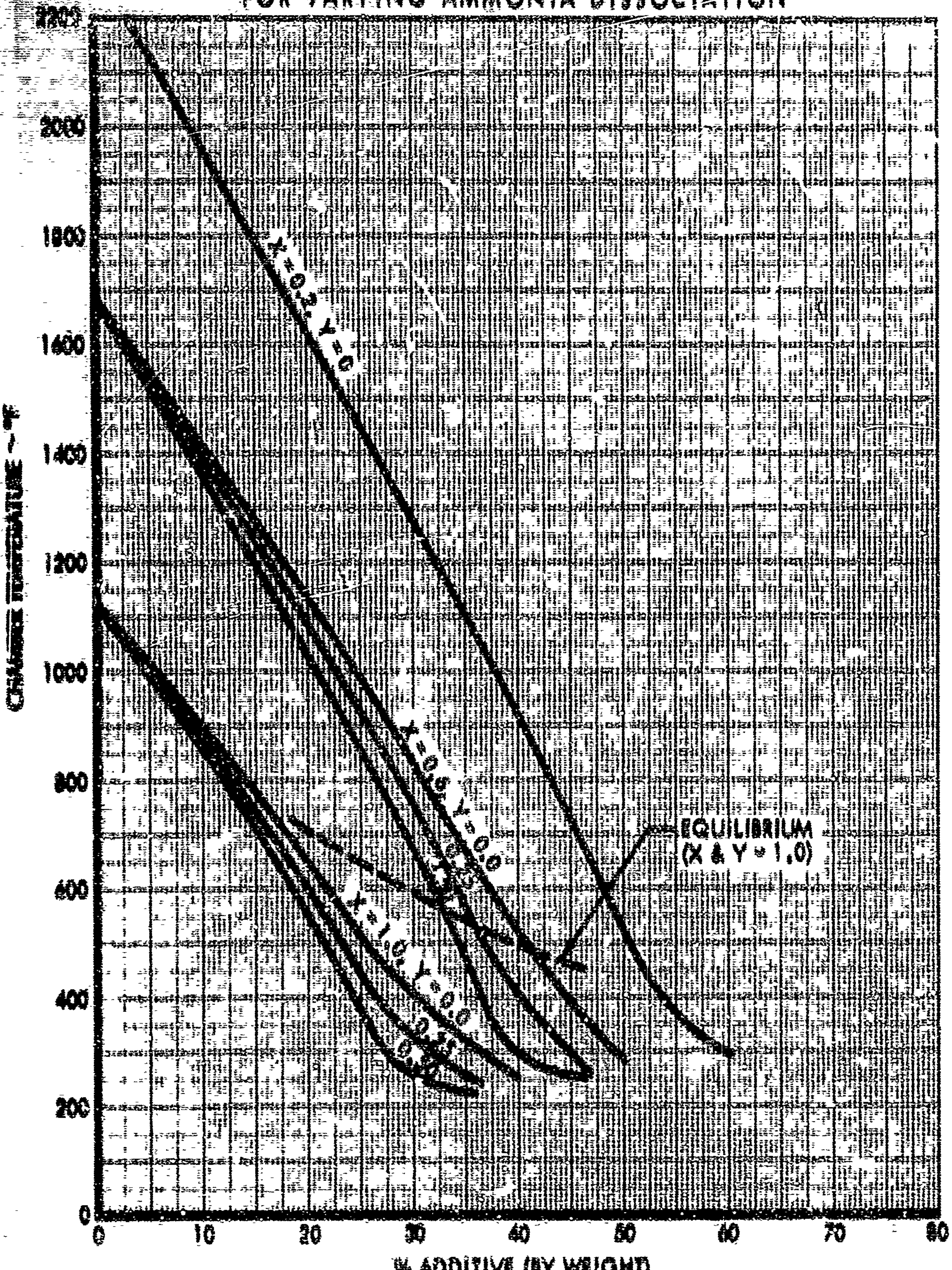


FIGURE 7

51044

51039-1

PERFORMANCE OF THE HYDRAZINE - AMMONIA SYSTEM AS A FUNCTION OF TEMPERATURE AND NH_3 DISSOCIATION

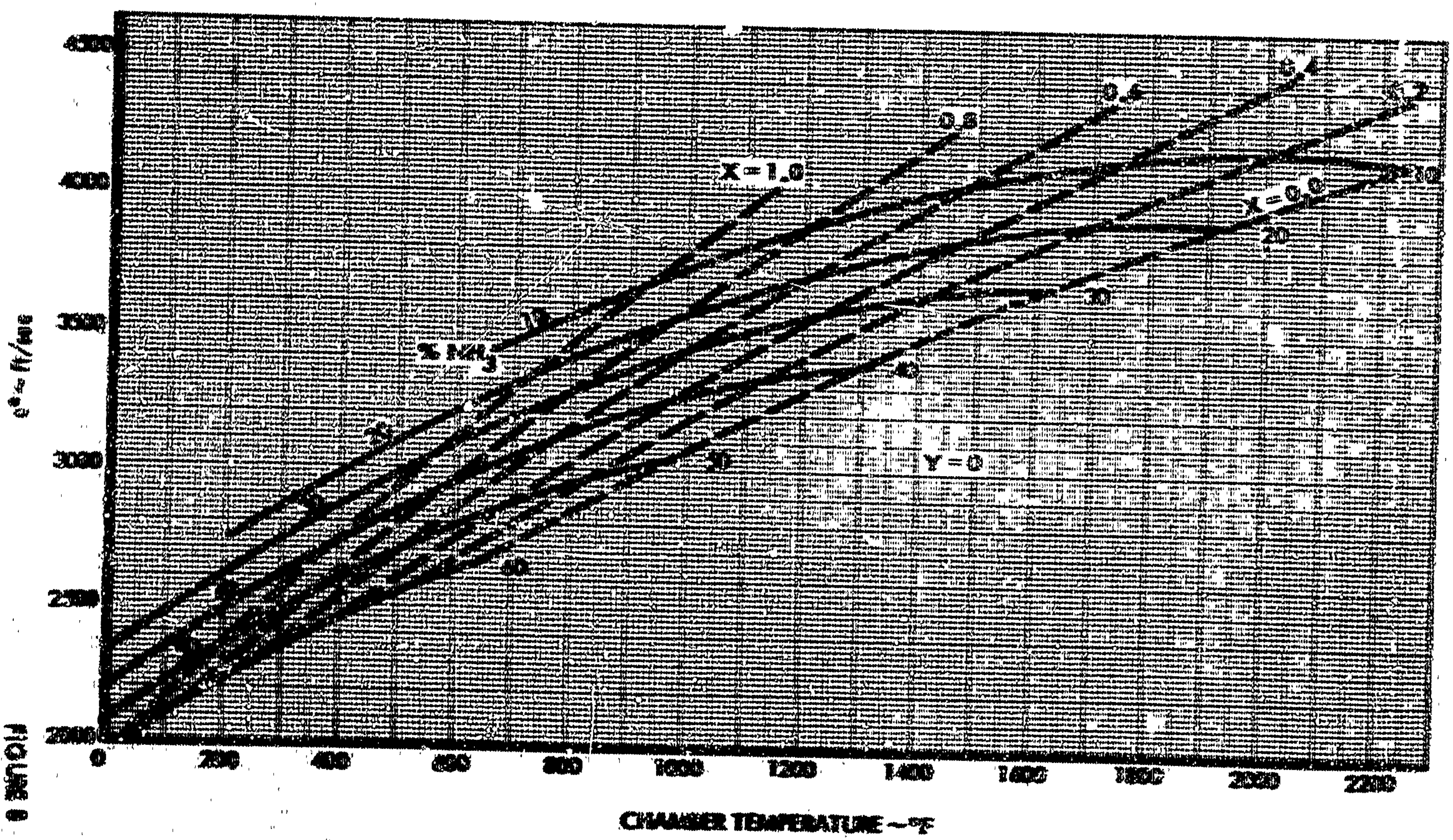
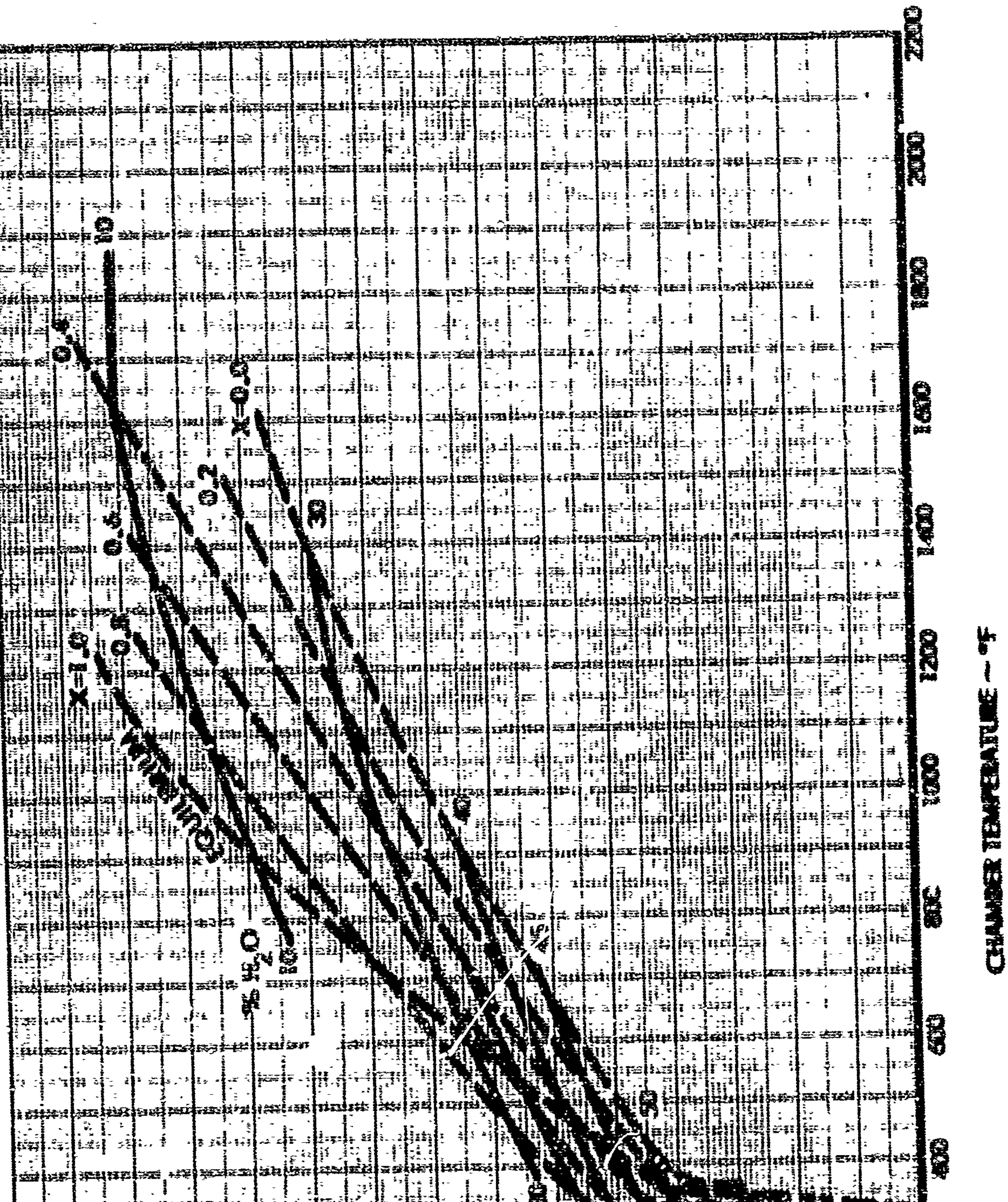


FIGURE 8



PERFORMANCE OF THE HYDRAZINE - H_2O SYSTEM AS A FUNCTION OF TEMPERATURE AND NH_3 DISSOCIATION

FIGURE 9

51035

PERFORMANCE OF THE HYDRAZINE - EQUAL WT % H_2O AND NH_3 SYSTEM AS A FUNCTION OF TEMPERATURE AND NH_3 DISSOCIATION

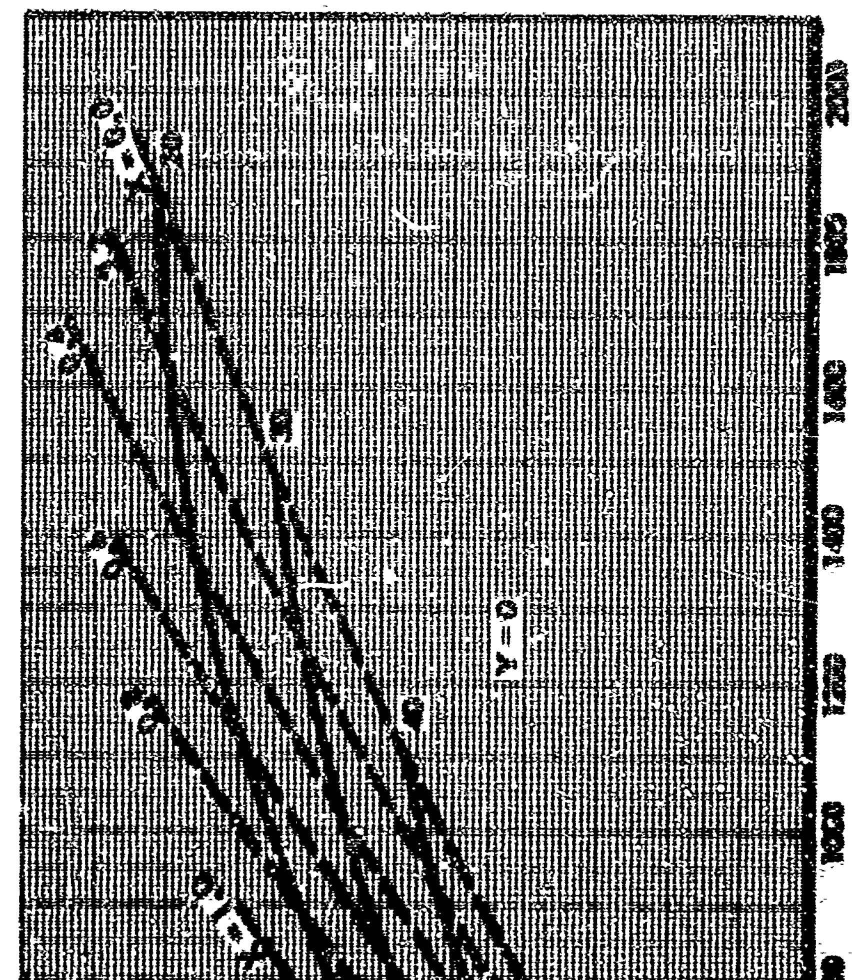


FIGURE 10

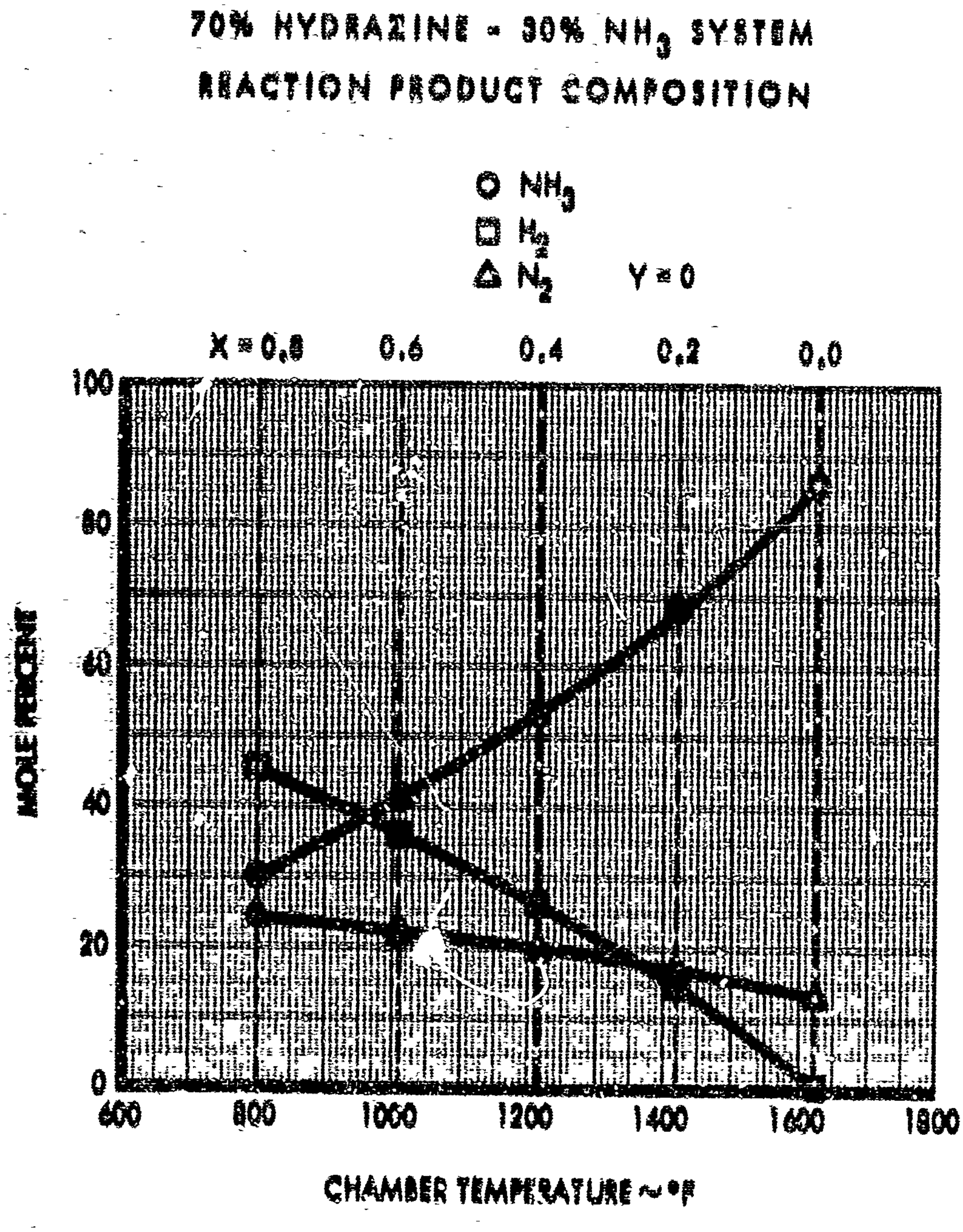
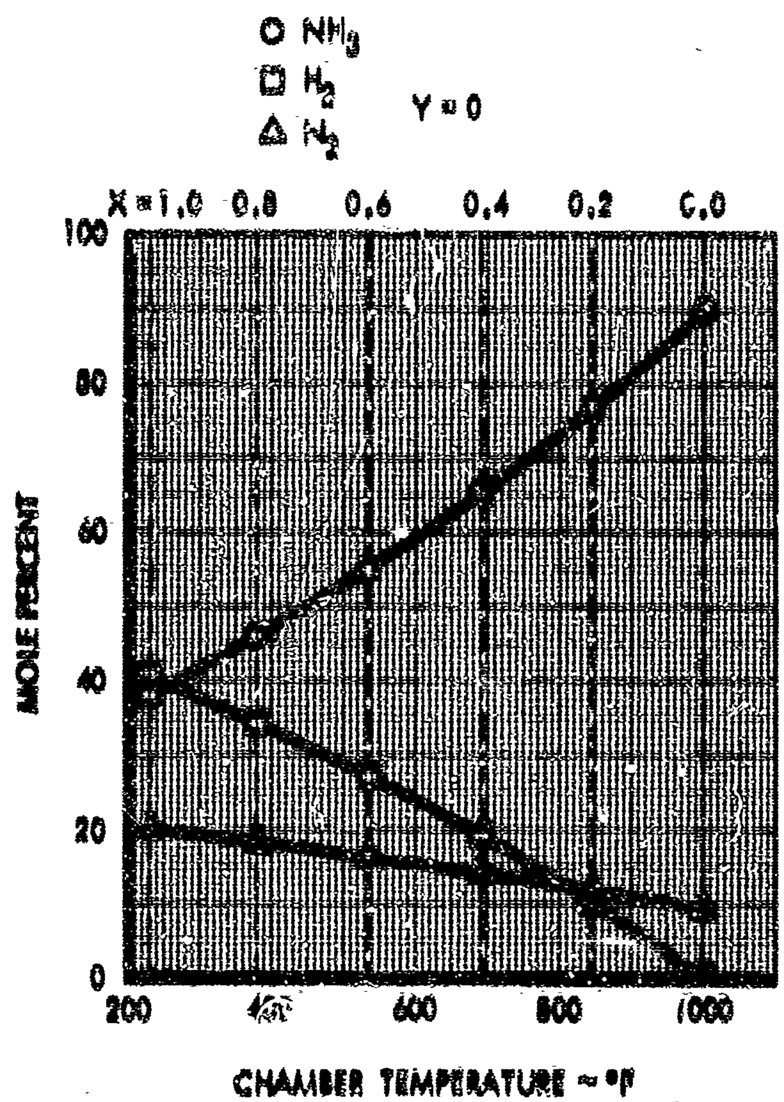


FIGURE 11

51041-1

50% HYDRAZINE - 50% NH_3 SYSTEM
REACTION PRODUCT COMPOSITION



60% HYDRAZINE - 40% NH_3 SYSTEM

REACTION PRODUCT COMPOSITION

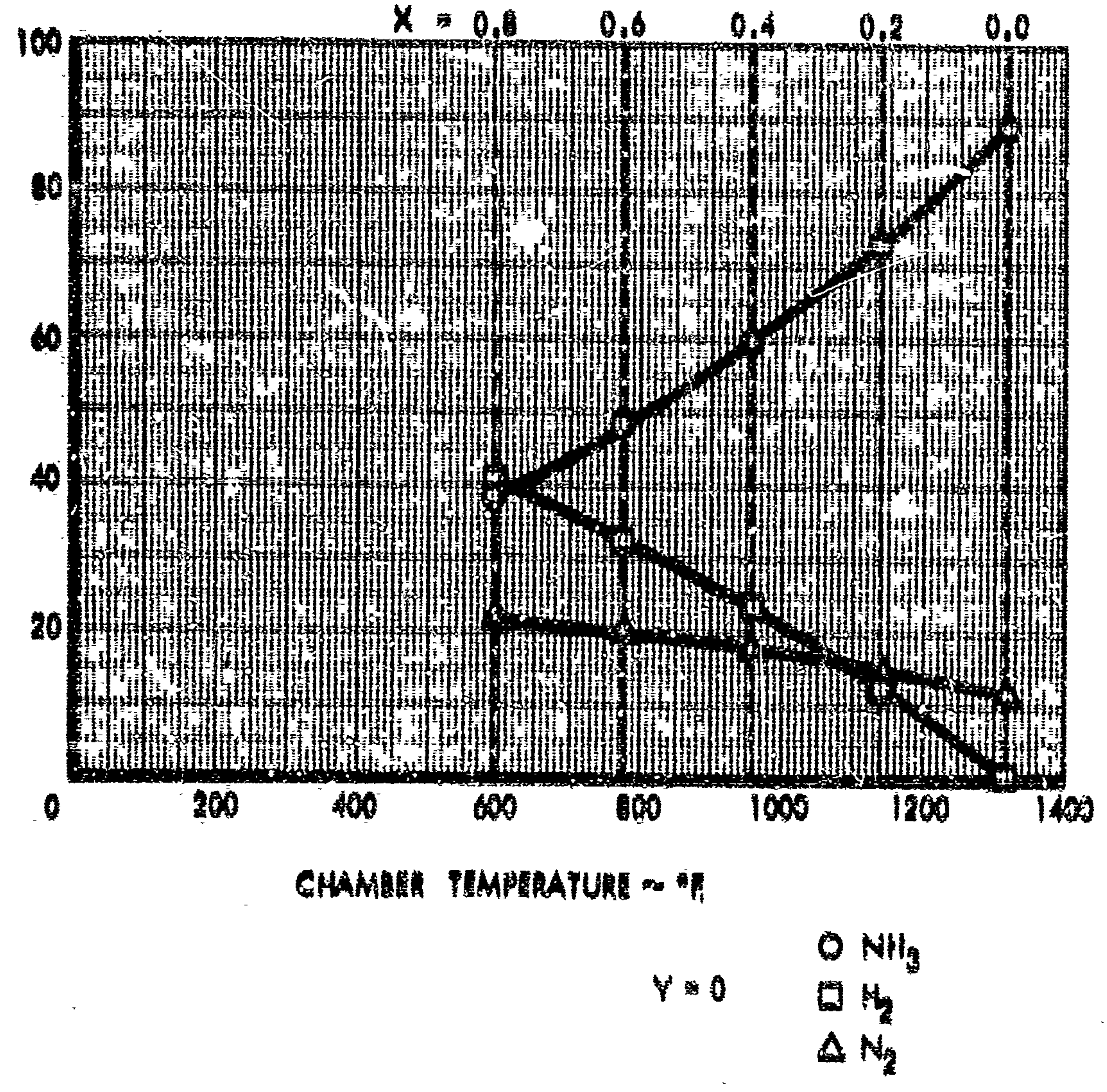


FIGURE 13

51046-1

70% HYDRAZINE - 30% H_2O SYSTEM

REACTION PRODUCT COMPOSITION

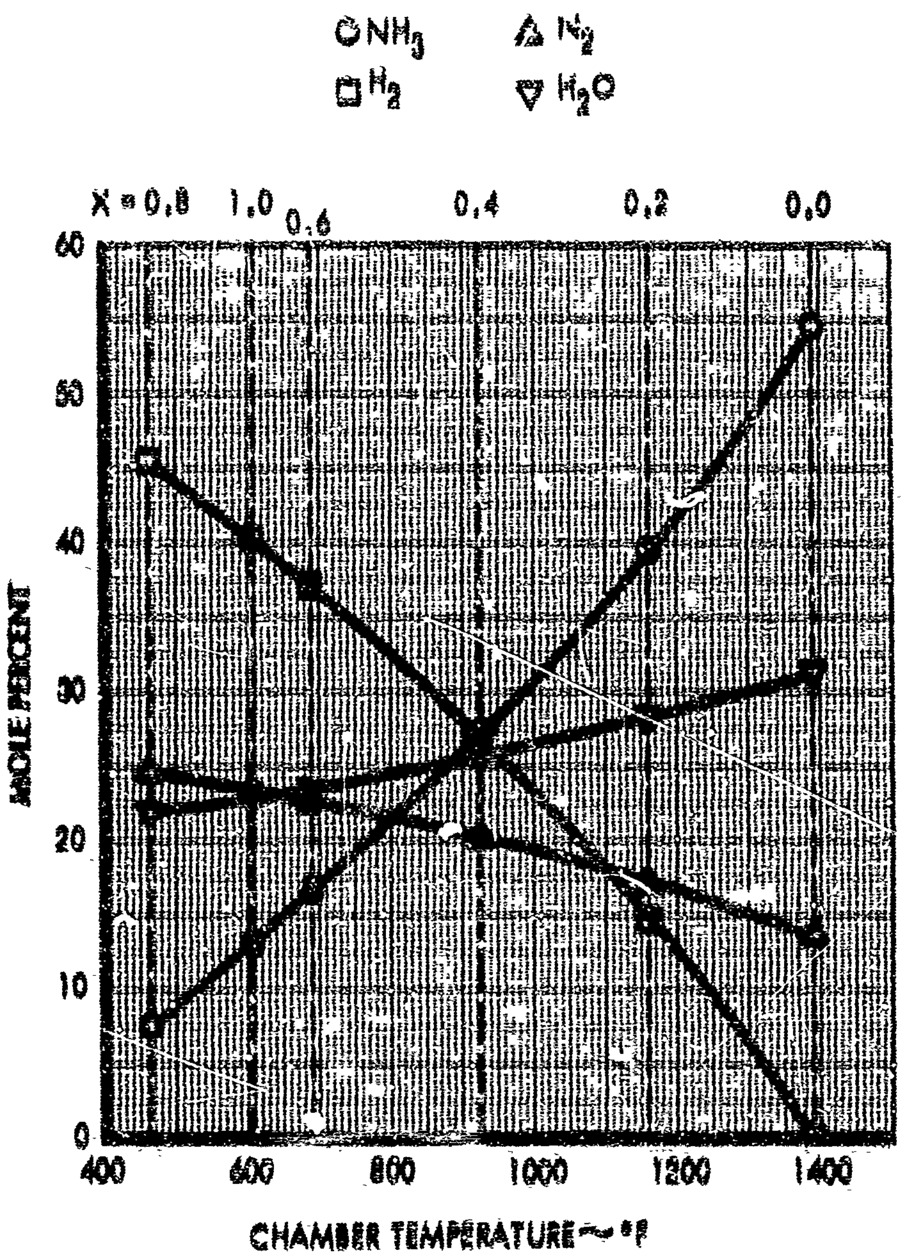
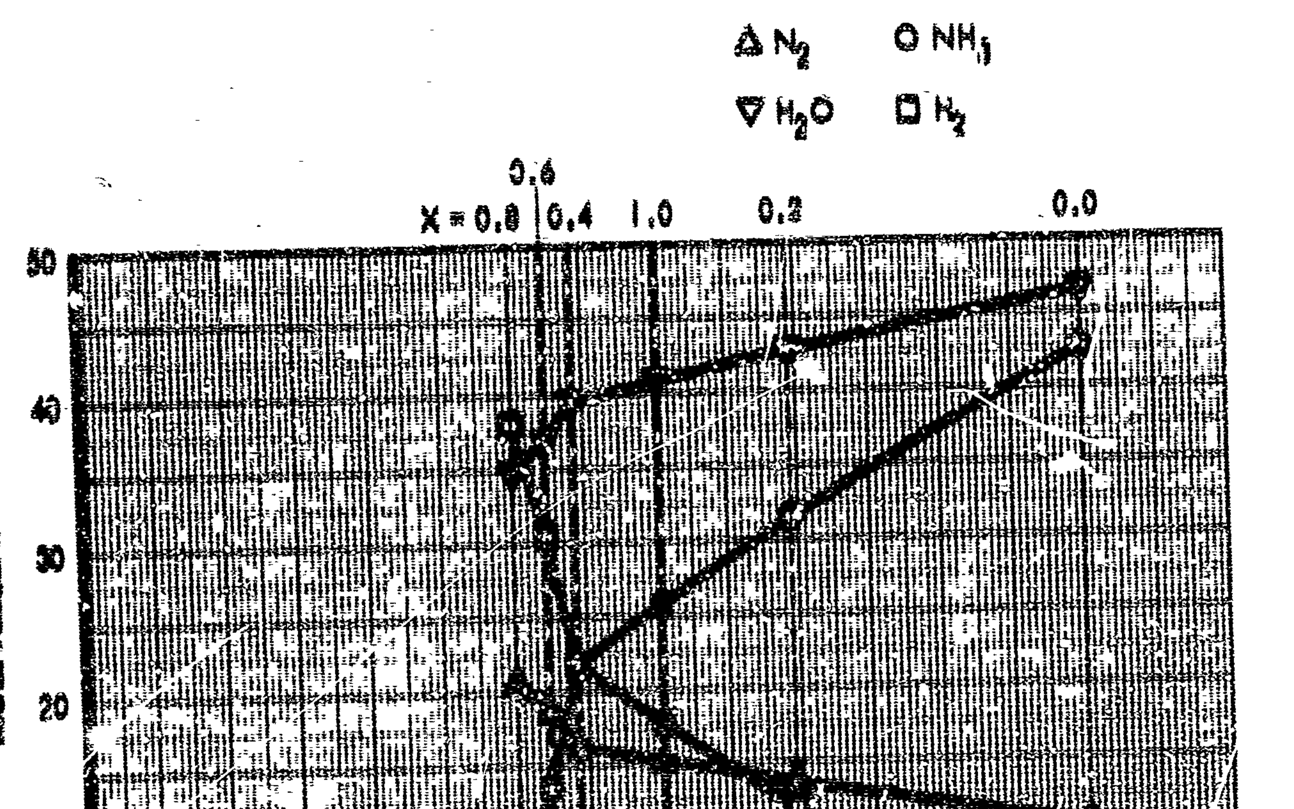


FIGURE 14

55% HYDRAZINE - 45% H_2O SYSTEM

REACTION PRODUCT COMPOSITION



51036-1

FIGURE 15

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13. ABSTRACT

The objective of this program was to characterize monopropellant hydrazine-based monopropellants which, by the use of ammonia and ammonia-water diluents, are capable of producing clean, low temperature gases when passed through a catalytic decomposition chamber. During the course of the 12-month program, thermochemical calculations were performed on a large number of cases involving various compositions of hydrazine, ammonia, and water. The effect of varying the amount of ammonia dissociation was investigated in the above calculations. Based upon the results of the thermochemical calculations and preliminary physical property testing, seven different solutions composed of various concentrations of hydrazine, water and/or ammonia were selected for further evaluation. The freezing points of the solutions were determined; and the vapor pressures, densities, and viscosities were measured over a wide temperature range. A low temperature gas generator was designed to produce approximately 60 standard cubic feet of gas per minute and to operate at a nominal chamber pressure of 300 psi. This gas generator was fired with each of the seven monopropellants in order to determine their steady state performance characteristics. In addition, a 1 lbf gas generator thruster was fired in pulse mode operation at various pulse widths and duty cycles with each of the seven monopropellants. The complete test results are presented in tabular form.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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Gas Generator						
Propellants						
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Hydrazine						

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